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THE EFFECT OF MECHANICAL THRESHING PARAMETERS ON KERNEL DAMAGE AND THRESHABILITY OF WHEAT

by

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A THESIS

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FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Effect of Mechanical Threshing Parameters on Kernel Damage and Threshability of Wheat" submitted by Frank Martin Vas in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

The principal objective of this project was to investigate the effects of the mechanical threshing parameters of cylinder speed, concave clearance and feed rate on threshability and kernel damage of wheat. The investigation was carried out using a stationary threshing unit designed for the purpose of performing threshing experiments in a laboratory. Statistical methods of analysis of variance and multiple regression were used to analyse the data. Partial derivatives were used to determine if a minimization of grain loss would occur within the boundaries set out in the investigation. The following results and conclusions were obtained:

1. Variations in threshability are significantly affected by cylinder speed and concave clearance. Increasing cylinder speed and decreasing concave clearance increases the percentage threshability.
2. Variations in mechanical kernel damage are significantly affected by cylinder speed, concave clearance and feed rate. Increasing cylinder speed, decreasing concave clearance and decreasing feed rate cause an increase in percentage mechanical kernel damage.
3. Percentage threshability (Y_T) and cylinder speed (X_S), concave clearance (X_C) and cylinder speed X concave clearance interaction ($X_S X_C$) were found to be related by the following regression equation:

$$Y_T = A_0 + A_1 X_S + A_2 X_S^2 + A_3 X_C + A_4 X_S X_C$$

where A_0 is a constant and A_1, A_2, A_3, A_4 are

partial regression coefficients.

4. Percentage mechanical damage (Y_D) and cylinder speed (X_S) and cylinder speed X concave clearance interaction ($X_S X_C$) were related by the following regression equation:

$$Y_D = B_0 + B_1 X_S + B_2 X_S^2 + B_3 X_S X_C$$

where B_0 is a constant and B_1, B_2, B_3 are partial regression coefficients.

5. A minimization of grain loss did not occur within the levels of the mechanical parameters considered in the project but it was indicated that such a minimum may be found if cylinder speeds lower than 4300 ft./min. were considered.

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1. INTRODUCTION

1.1 Harvesting and Threshing Methods

When primitive man turned to agriculture as a way of life, he began planting and harvesting crops. Timeliness in getting the seed in the ground was not of prime importance but the harvest was very sensitive to delay. In spite of this, little progress was made in harvesting methods from Biblical times to the early 1800's. The crop was cut using a sickle, scythe or cradle and then threshed using a "flail". The flail was later replaced to some extent by "animal treading". The introduction by Daniel Massey in 1830[20] of the first stationary threshing machine into Canada, marked the beginning of mechanization of harvesting methods. The spike-tooth cylinder and concave used in the unit was the counterpart of the flail used in earlier times. Between 1830 and 1930, threshing machines changed very little although modifications were made to accommodate combined cutting and threshing by using a portable, rather than a stationary unit. In the early 1930's, the rasp-bar cylinder[38] and concave emerged as the newest development in threshing devices. With the advent of gasoline engines, tractor drawn and self-propelled combine-harvesters were developed. Today, the rasp-bar cylinder is still the most common threshing device. Its retention in view of the technological advances in the farm machinery industry, indicates its value in the threshing process. Research has been done on alternative devices, such as the threshing cone[14], but these have failed to replace the rasp-bar cylinder thus far.

1.2 Basis for the Study

Considering the extensive use of the combine-harvester today in

Alberta, it was decided to conduct research on some of the mechanical threshing parameters to determine the manner in which they influence grain threshability and kernel damage. Furthermore, it was felt that farmers adjust threshing parameters on the basis of threshability without due regard to a consideration of mechanical kernel damage. Resulting kernel fragments could well be expelled from the combine by pneumatic separation and go unnoticed by the operator. This would imply that by setting parameters to remove all the grain from the ears, there may be a resulting increase in kernel damage which could more than offset the benefit of increased threshability.

The parameters for the study (cylinder speed, concave clearance and feed rate) were selected for two reasons, firstly because of their suspected importance in the threshing process and,secondly because they are usually easy to adjust. The controls for these adjustments are usually situated within easy reach of the combine operator and do not require stoppage of the machine to change the setting.

It was felt that information gained concerning the influence of the parameters on threshability and grain damage could provide insight into an assessment of related problems encountered in the field, even though the research was carried out in the laboratory under fixed conditions. It was also realized that numerous variables are encountered in the field while this research study was restricted to only three factors. By carrying out threshing trials in the laboratory, strict control was possible to ensure that grain losses were minimized and, thus, it was possible to retain most kernel fragments which could easily be lost in a field study.

1.3 Objectives

The following objectives were considered in this research project:

1. To design and construct a stationary threshing unit for harvesting grain samples in the laboratory.
2. To develop a convenient and workable procedure for cleaning the threshed samples in the laboratory with a view towards minimizing losses of kernel fragments.
3. To develop a suitable experimental procedure for carrying out threshing trials in the laboratory incorporating techniques of randomization and replication.
4. To determine the influence of the independent variables (parameters) on threshability and grain damage, using statistical procedures involving analysis of variance as well as correlation and regression techniques.
5. To determine if some level of the variables (parameters) considered would result in an optimum situation of high threshability and low kernel damage.

2. REVIEW OF LITERATURE

2.1 Threshing Experiments

Investigations of the parameters involved in the harvesting of small grains are found in the literature as early as 1934 when Bainer and Borthwick[8] studied mechanical injury to seed beans. DeLong and Schwantes[19] in 1942, and Arnold[2] in 1959 investigated the harvest damage incurred by barley kernels; the former using kernel breakage as a damage indicator and the latter using kernel germination. Bainer, et al[9], studied the effect of cylinder speed on damage to alfalfa seed as determined by germination tests. Kolganov[34], in his studies on double threshing, considered the effect of cylinder speed and concave clearance on the threshability and incidence of damaged kernels in wheat.

Although the investigations were performed using different seed crops under different conditions, the general conclusions reached were similar. In all cases, cylinder speed emerged as the most significant factor influencing threshability and seed damage. Concave clearance, although of lesser significance, was still considered to be an important factor.

Arnold[3] carried out one of the most extensive studies on threshing parameters. He performed a series of experiments in the laboratory using a stationary "threshing rig" designed to accommodate changes in physical dimensions as well as cylinder speed and concave clearance adjustments. Some of the factors considered were cylinder diameter, number of cylinder beater bars, concave length, grain moisture content, rate of feed, method of crop presentation (heads first or butts first), cylinder speed and concave clearance as well as varietal differences.

Broken grain counts were carried out in the laboratory on 100 gram

samples. A brief summary of the results obtained follows, with specific reference to the factor concerned.

Moisture Content

Grain breakage was consistently greater at the lowest moisture levels (13.7% - 15.1%)*. Superior grain condition was observed in the "safe zone" between 17.5% and 22.0% moisture. Grain breakage was more common in Capelle Desprez wheat than in Koga 2 wheat.

In general, an increase from 15% to 25% moisture content in the wheat, doubled the average cylinder loss which was an indication of the lower threshability at the higher moisture level.

Direction of Feed

Direction of crop presentation to the cylinder had no effect on the occurrence of broken wheat kernels. However, threshability was greatly improved when the material was presented heads first as opposed to butts first.

Feed Rate

The feed rate was varied in two ways: by altering the conveyor speed with a uniform crop thickness and by varying the crop thickness at a constant conveyor speed. Both methods were found to work satisfactorily. Within the range of feed rates examined (72 lbs./min. to 240 lbs./min.), there was no evidence of changes in threshability. There was slight evidence that low feed rates resulted in a higher number of broken grains in the Capelle Desprez wheat.

Cylinder Diameter and Bar Spacing

It was concluded that the influence of these factors on grain damage and threshing efficiency was insignificant in the study.

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* In this thesis all moisture contents are given on a wet-weight basis.

Cylinder Speed

The Capelle Desprez wheat was found to break fairly readily and complete avoidance of breakage at the low moisture contents (15%) was only possible with cylinder speeds below 3500 ft./min. Koga 2 wheat was found to be more resistant to breakage, indicating varietal differences in shattering resistance.

Cylinder speed was considered to be the most important factor influencing threshing efficiency and thus threshability. Increasing the cylinder speed from 3500 ft./min. to 6500 ft./min. reduced the amount of material unthreshed, but 100% threshing efficiency was never achieved. However, at 13.7% moisture content and 6500 ft./min. cylinder speed, the threshability was 99.50%.

Mean Concave Clearance

Smaller clearances appeared to lead to higher kernel breakage at the lower moisture contents but the results were inconclusive.

Increasing the clearance from 1/4 in. to 5/8 in. showed a significant tendency to increase the amount of unthreshed grain, even though the unthreshed portion was considered to be negligible in practical terms.

Concave Length

For an increase in concave length, the kernel damage increased with approximately three times as many broken or chipped kernels when using the 20 in. concave as using the 6.7 in. concave.

Less than 1% of the grain was unthreshed using the 20 in. concave at all speeds over 3500 ft./min. Using the 6.7 in. concave, unthreshed portions ranged from 5% at a speed of 3500 ft./min to 2% at 4500 ft./min. to less than 1% at either 5500 ft./min. or 6500 ft./min.

In conclusion, Arnold stated that the reduction or elimination of

kernel damage depends on the use of lower cylinder speeds but this results in a loss in threshing efficiency. A compromise situation must be achieved where damage is relatively low and threshability or threshing efficiency is high.

Arnold and Lake[5] extended the scope of the earlier study[3] to include a comparison of open and closed concaves. The closed grate concave produced four times as many broken grains as the open grate type. Differences in the threshing effect produced by the two concave types were negligible.

King and Riddolls[32] studied kernel damage in wheat and pea seed. They originally intended to use a commercial type harvester for the experiments but found it unsatisfactory due to:

1. the time required to clean out between treatments,
2. the excessively large quantity of material required for each run, and
3. the excessive time required to adjust concave clearances and cylinder speeds.

In view of the difficulties encountered, King[31] developed a small, stationary harvester for the purposes of his research.

The experiments were carried out over three years (1953, 1954 and 1955) using the same general procedure each year.

In the 1953 trials, differences in mean damage at different cylinder speeds were found to be highly significant with a "significant linear regression". The differences at different concave clearances were also significant but there was no "significant linear regression". Over the range of cylinder speeds used (1000 rpm to 1400 rpm), for each 50 rpm increase, the percent visible damage increased by 0.95± 0.32.

The visible damage ranged from 1.8% to 16.0%.

In the 1954 trials, lower cylinder speeds and wider concave clearances were used. The cylinder speeds ranged from 600 to 1200 rpm in 100 rpm increments and the concave clearances ranged from 1/8 to 9/32 in. in 1/32 in. increments. The different concave clearances and cylinder speeds showed highly significant differences in damage with the linear regression also being highly significant for both factors. For each 1/32 in. decrease in concave clearance, the visible damage increased by 0.93±0.42. The visible damage ranged from 0.6% to 18.8%.

In the 1955 season, cylinder speed was found to be a significant factor as was the cylinder speed and concave clearance interaction. However, concave clearance was not significant. The linear regression for cylinder speed was significant, with each 100 rpm increase causing visible damage to increase by 3.66±0.62.

In the 1956 and 1957 crop seasons, King and Riddolls[33] extended the previous study[32] to determine the effect of variations in moisture content on visible damage. For the trials, concave clearance remained fixed at 3/16 in. and cylinder speeds were 1200 and 1400 rpm in 1956 and 1000, 1200 and 1400 rpm in 1957.

In 1956, the trials indicated that visible damage at either 1200 or 1400 rpm was much lower at 19.2% moisture content than at 13.2% moisture content. Both moisture content and cylinder speed were significant with no "significant linear regression".

In 1957, using a narrower moisture range (15.1% to 20.8%), only cylinder speed was significant with no "significant linear regression".

Caldwell and Mitchell[16], although being mainly concerned with storage effects on grain harvested using different concave clearances

and cylinder speeds, did an analysis in the initial stages to ascertain the incidence of damaged wheat kernels immediately after harvest.

The visual damage analysis was carried out on 200 grain samples using a microscope (X20). Any kernel that had a break in its surface was considered to be damaged. The results indicated that the greatest incidence of damaged grains occur at the lowest moisture level (<16%) and at the highest cylinder speed. At all moisture levels, the lowest cylinder speed was associated with the least amount of damage. It is interesting to note that visual damaged ranged from 29.7% to 61.2%.

Arnold and Jones[6] carried out experiments in the field to determine grain damage resulting from given cylinder speeds and moisture contents. Combine-harvester users were selected at random, and as each was harvesting his crop, samples were taken from the machines at spaced intervals. The cylinder speed was recorded for each run. Moisture determinations and broken grain counts were done in the laboratory on the samples collected. Broken grain included all grains showing any form of chipping or breakage.

The mean moisture content of the samples collected was 19.6%, the range being from 16.1% to 31.8%. The mean cylinder speed was 5381 ft./min. with a range from 4335 ft./min. to 6447 ft./min. The percentage broken grains varied from 0.7% to 10.6% with a mean of 3.9%. A multiple regression analysis was carried out treating moisture content and cylinder speed as independent variables and broken grains as dependent variable. The equation arrived at is as follows:

$$\text{broken grains} = 1.451 + 0.00144 \text{ cylinder speed} - 0.26992 \text{ moisture content.}$$

The correlation coefficient between broken grains and cylinder speed was

0.306 and that for broken grains and moisture content was 0.305, both being significant.

Investigations to study the influence of speed of impact on the damage to individual wheat kernels have been performed by various researchers[26,36]. The results obtained indicated that speed of impact was the prime cause of kernel damage. It was further indicated that in a threshing unit, the speed of impact is imparted to the grain kernels by the fast moving cylinder beater bars. This supports the idea that cylinder speed is the main factor influencing grain damage.

2.2 Laboratory Threshing Units

A review of the literature concerning development of laboratory threshing units[13,25,27,31,44], indicated some desirable characteristics that should be incorporated into such a unit for the purposes of experimentation. Some of these characteristics follow.

1. Component parts such as the cylinder and concave should be similar to existing commercial types.
2. There should be simplicity of overall design to ensure that only the components under study can influence the value of the required measurements. For example; if cylinder speed and concave clearance effects are to be studied in terms of grain damage, the design should be such that the grain is not damaged before it reaches the cylinder concave unit.
3. The unit should be self-cleaning to prevent contamination between different treatments.
4. Provision should be made for rapid, accurate and simple adjustment of settings like cylinder speed and concave

clearance.

5. Provision should be made to ensure recovery of a maximum of material.
6. Power sources should be set up in such a manner that all components can be brought up to full speed before feeding the material to be threshed into the unit. This is necessary in order to eliminate beginning and ending effects.

2.3 Assessing Kernel Damage

The United States Official Grain Standards[39] define damaged kernels as "kernels and pieces of kernels of wheat which are heat damaged, sprouted, frosted, badly ground damaged, badly weather damaged, moldy, diseased or otherwise materially damaged". The only specific reference made to mechanical kernel damage is in terms of shrunken and broken kernels, these including "all kernels and pieces of kernels of wheat and other matter that will pass readily through a 0.064 by 3/8 inch slotted hole sieve". This definition of mechanical damage is inadequate since it excludes chipped kernels and broken half kernels.

Mechanical damage measures and definitions are numerous in the literature as pertains to harvesting of seed crops. Agness[1] attempted to analyze the problems of measuring mechanical damage to corn kernels. He stated, "defining corn kernel damage in terms acceptable to all segments of the corn industry is an impossible task". This is why there is no single measure which is strictly adhered to today. Agness went on to discuss various methods for determining mechanical damage. He divided damage evaluation procedures into discrete and bulk tests, with discrete tests being those which considered each individual kernel and bulk tests being those based on the sample as a whole. The principal disadvantage

of using bulk methods was that the effect of a few bad kernels could be indistinguishable among the large bulk of good kernels and damage differences could be obscured by experimental errors. In the discrete tests, a principal advantage was that even one bad kernel could be found, although a limitation of the visual separation of damaged kernels was that human judgement and fatigue could influence results.

Mechanical damage as ascertained by visual examination has been a common discrete test used by many investigators in threshing experiments involving corn[10,15,30] and wheat[3,32,34] as well as other seed grains[19]. A small sample taken from the bulk was hand-sorted into whole kernels and cracked, chipped or broken kernels. This method gave desirable results since all kernels being damaged in any way could be detected, whereas a screening process as laid out in the Official Grain Standards may exclude half kernels or whole kernels with small fragments chipped from the surface.

3. EXPERIMENTAL PROCEDURE

The experimental trials were run at the University of Alberta, Department of Agricultural Engineering Machinery Laboratory using a stationary threshing unit.

3.1 Definitions and Measurements

The variables considered in this experiment along with a definition of each and the units of measurement used are listed below.

3.1.1 Dependent Variables

Y_T = Threshability - Percentage by weight of wheat kernels removed from the ear during initial treatment.

Y_D = Kernel Damage - Percentage by weight of wheat kernels that show mechanical damage as determined by visual examination, including any broken, cracked or chipped kernels.

3.1.2 Independent Variables*

X_S = Cylinder Speed - Speed of the cylinder measured in revolutions per minute.

X_C = Concave Clearance - The distance between the cylinder beater bar and the front concave bar measured in inches.

X_F = Feed Rate - The total material, including grain, straw and chaff, which is fed to the threshing unit, measured in pounds per minute.

---

* Variables refer to the threshing parameters.

3.2 Materials and Equipment

3.2.1 Threshing Material

The material used throughout the experiment was the hard red spring wheat variety, Park. The standing wheat crop from a 10 acre field was obtained from a farm in the Leduc, Alberta area. Pertinent variety characteristics[43] were "good" resistance to lodging and shattering. The variety was considered easier to thresh than the common wheat variety, Thatcher. Park wheat is grown mainly in Alberta in the Lacombe, Evansburg and Peace River areas.

The threshing material had an average grain to straw ratio* of 1.00/1.71 and an average grain moisture content of 10.4% (wet basis).

3.2.2 Threshing Unit

Because the research was carried out in the laboratory, a stationary threshing unit was needed. Such a unit was designed and constructed, with the preliminary design work carried out by Professor H.P. Harrison of the Department of Agricultural Engineering, University of Alberta, Edmonton.

A survey[29] carried out to ascertain the common features of the basic models of the 34 self-propelled combines sold in Western Canada, indicated some generalities in design. The rasp-bar cylinder was the most common threshing device. A majority of the combine models used an open grate concave with the number of concave bars ranging from 8 to 12. A "conventional" method of feeding the crop from the combine table to the cylinder was indicated. This method made use of the grain elevator as the main component, although intervening beaters could be fitted as options.

---

* Grain to straw ratio = grain weight/straw and chaff weight.

In view of the survey, all component parts used in the threshing unit were standard commercial type, specifically being those used in the Massey-Ferguson 205 self-propelled combine. It was felt the component parts of this combine model were indicative of the common features outlined in the survey. Furthermore, the relatively low capacity of the model in terms of material throughput, indicated that a reasonably small amount of material could be used for a given treatment.

A schematic diagram of the component parts of the threshing unit appear in figure 1. A photograph of the overall unit in the laboratory appears in figure 2.

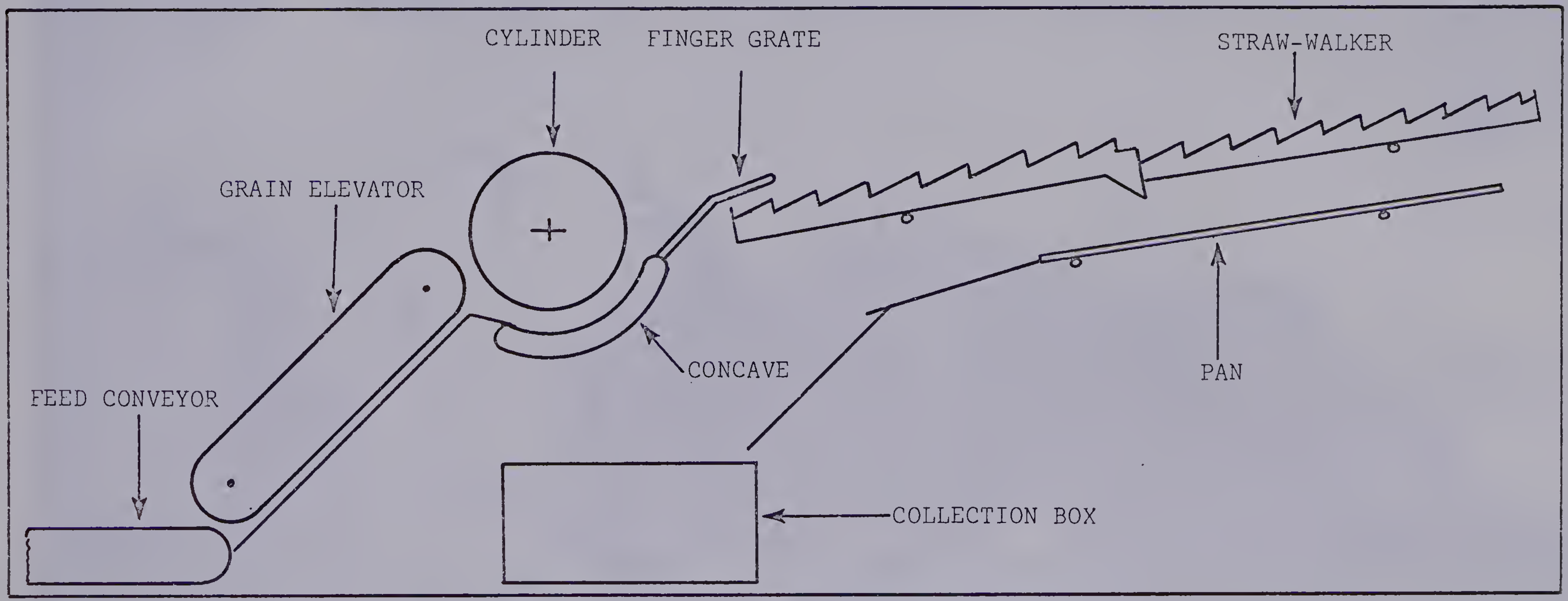

Figure 1: Schematic diagram showing the components of the laboratory threshing unit.

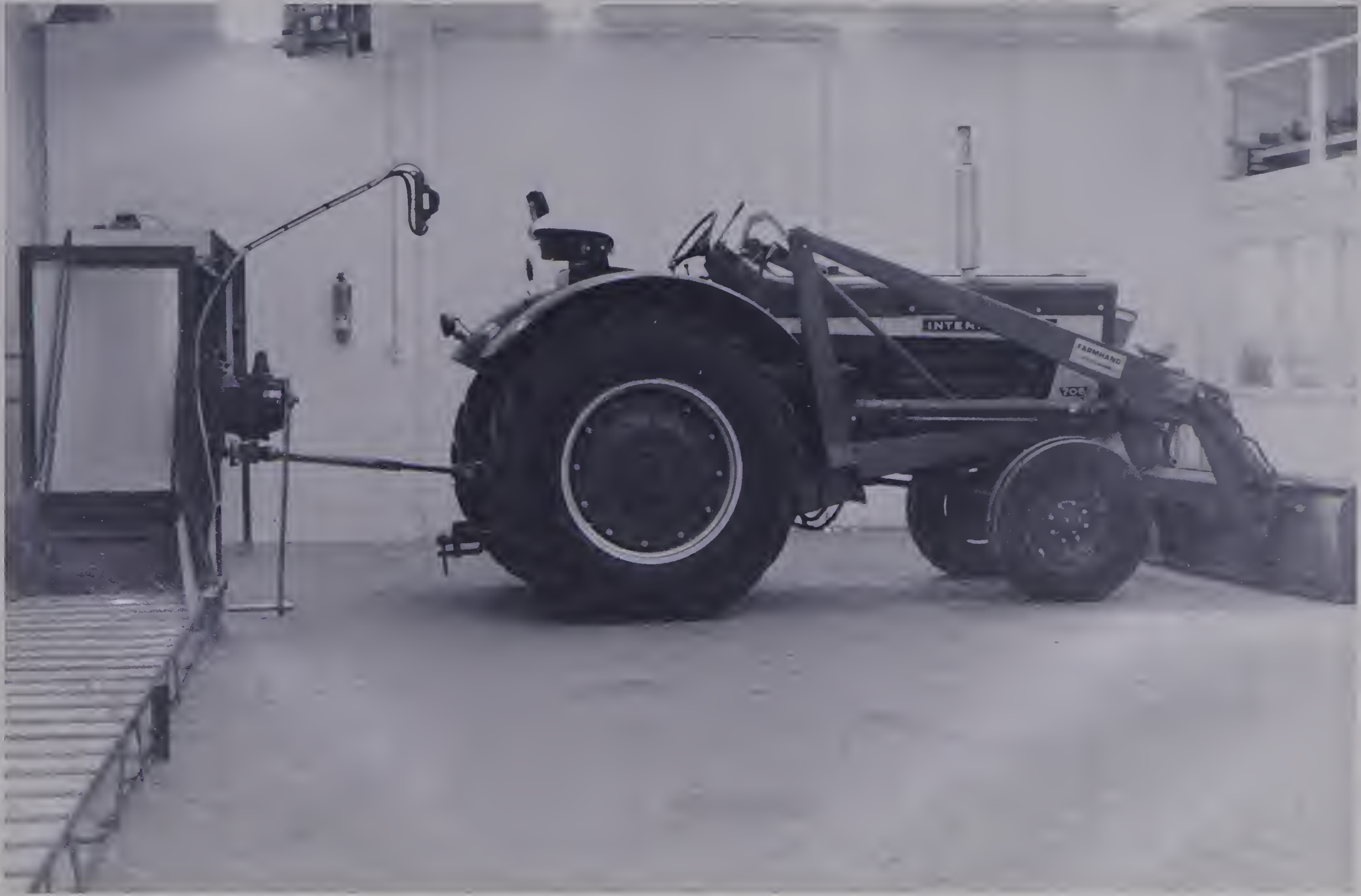

Figure 2: The laboratory threshing unit.

The cylinder used in the unit (figure 3) was the rasp-bar type, being 21 in. in diameter and 24 in. in width, having 8 beater bars spaced around its periphery. The concave was the open grate type, being 18 in. along the curvature and having 8 concave bars. The concave wires making up the grate were 1/4 in. diameter spaced 1/2 in. apart. The threshing material was fed to the cylinder by a grain elevator as shown in figure 3. The angle of entry of the material to the cylinder remained constant at 45°.

The only grain separation that occurred in the unit was that performed by the straw-walkers. Three, single step, 8.5 ft. long and 9 in. wide walkers were used with 1 ft. extensions being added to reduce grain loss. The material was conveyed by an oscillating pan under the walkers. This material as well as all the material falling through the concave openings was caught in a common collection box shown at A in figure 4. This mass of material collected was cleaned later using a separate unit.

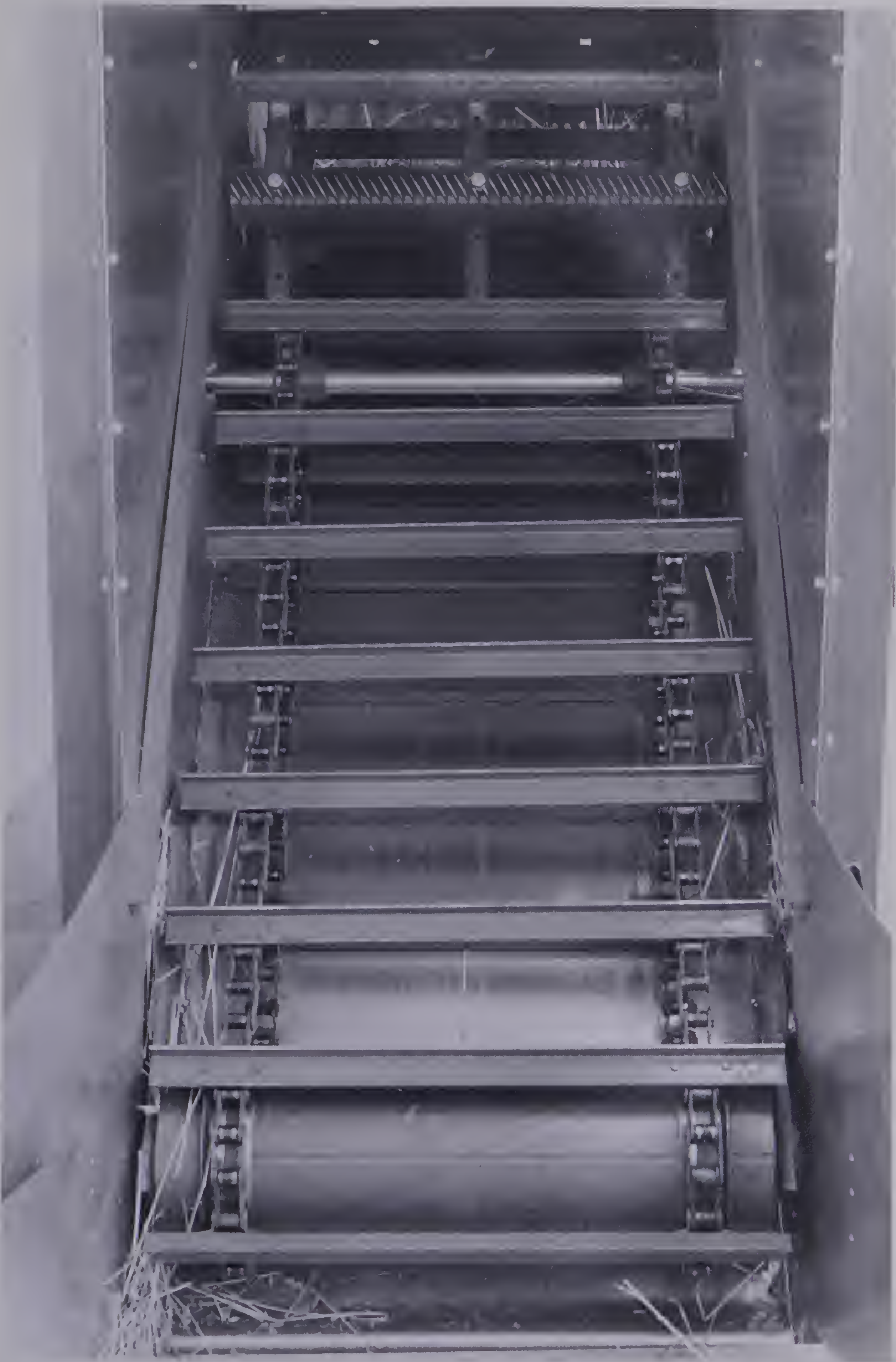

Figure 3: Rasp-bar cylinder and grain elevator used in threshing unit.

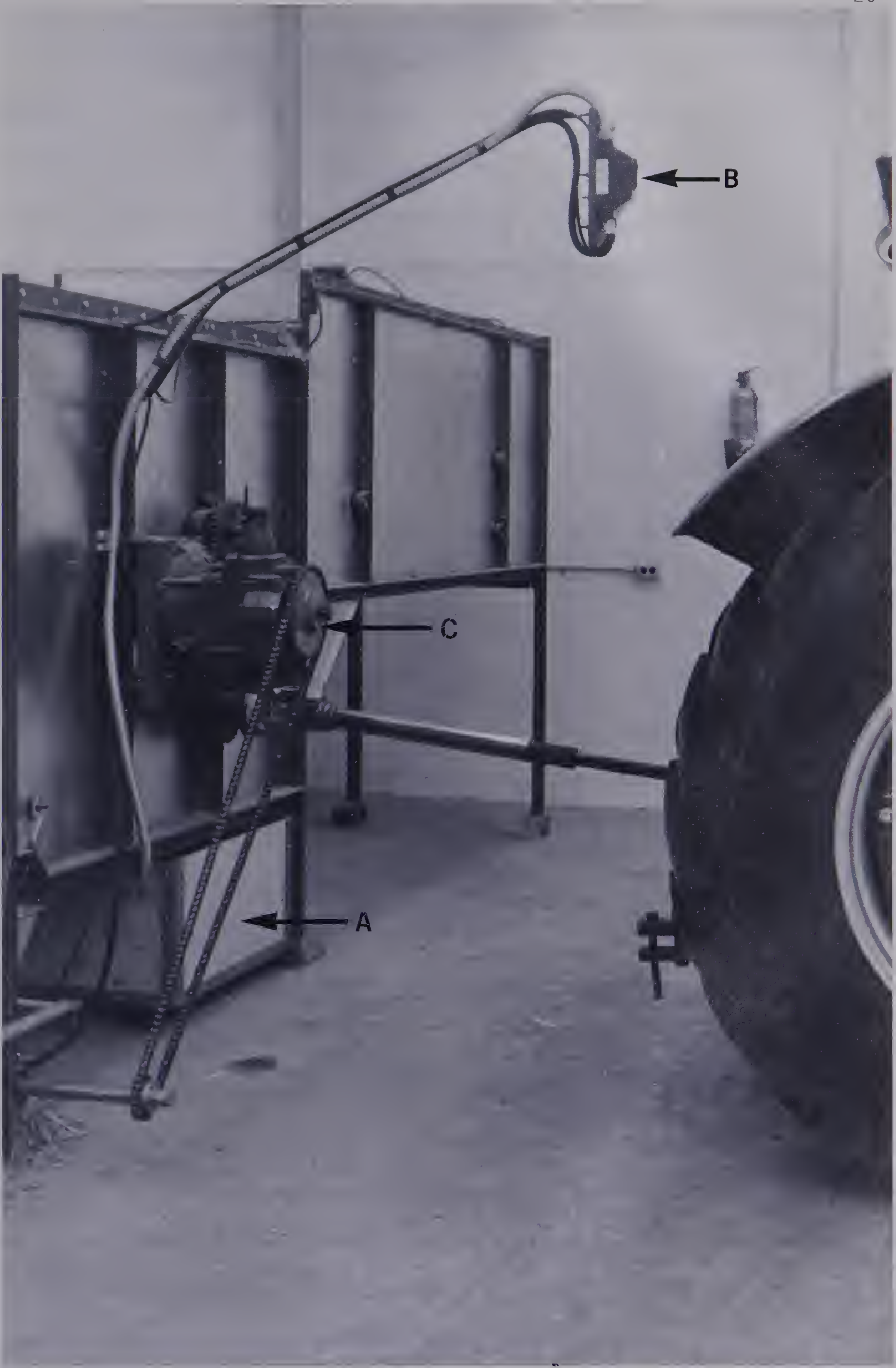

Figure 4: View of threshing unit showing: A - collection box
B - electrical control switches
C - feed conveyor drive sprocket.

The two electrical switches at B, figure 4, were used to control operation of the working components. One switch controlled the 3 horsepower electric motor which powered the grain elevator and feed conveyor. The other switch controlled the 1/2 horsepower electric motor which powered the straw-walkers and the oscillating pan under the walkers. The power-take-off shaft of an International Harvester 706, diesel tractor was used as the power source for the cylinder. The sprocket at C, figure 4, drove the feed conveyor. All drives were the sprocket and roller chain type.

The entire unit was housed in a sheet-metal enclosure, having all structural members on the outside to ensure the unit was self-cleaning and also to avoid possible between-treatment contamination. The use of the grain elevator and the absence of intervening beaters in the feed mechanism to the cylinder facilitated crop flow and ensured that no appreciable threshing or mechanical kernel damage could occur other than that resulting from the cylinder-concave. The use of independent power sources for the working components allowed them to be brought up to full speed before material was fed to the unit. The absence of cleaning facilities in the threshing unit allowed maximum recovery of material.

3.2.3 Feed Conveyor

A 50 ft. long and 3 ft. wide conveyor was built to feed the threshing material to the threshing unit. The conveyor, shown in figure 5, was made up of sections of slatted canvas attached together by a belt and buckle arrangement. The conveyor was stretched between two 6 in. rollers and slid on an angle iron frame made up in 10 ft. sections, bolted together for ease of assembly and disassembly. The conveyor was made as long as possible (within the laboratory length limitations) to reduce beginning and ending effects.

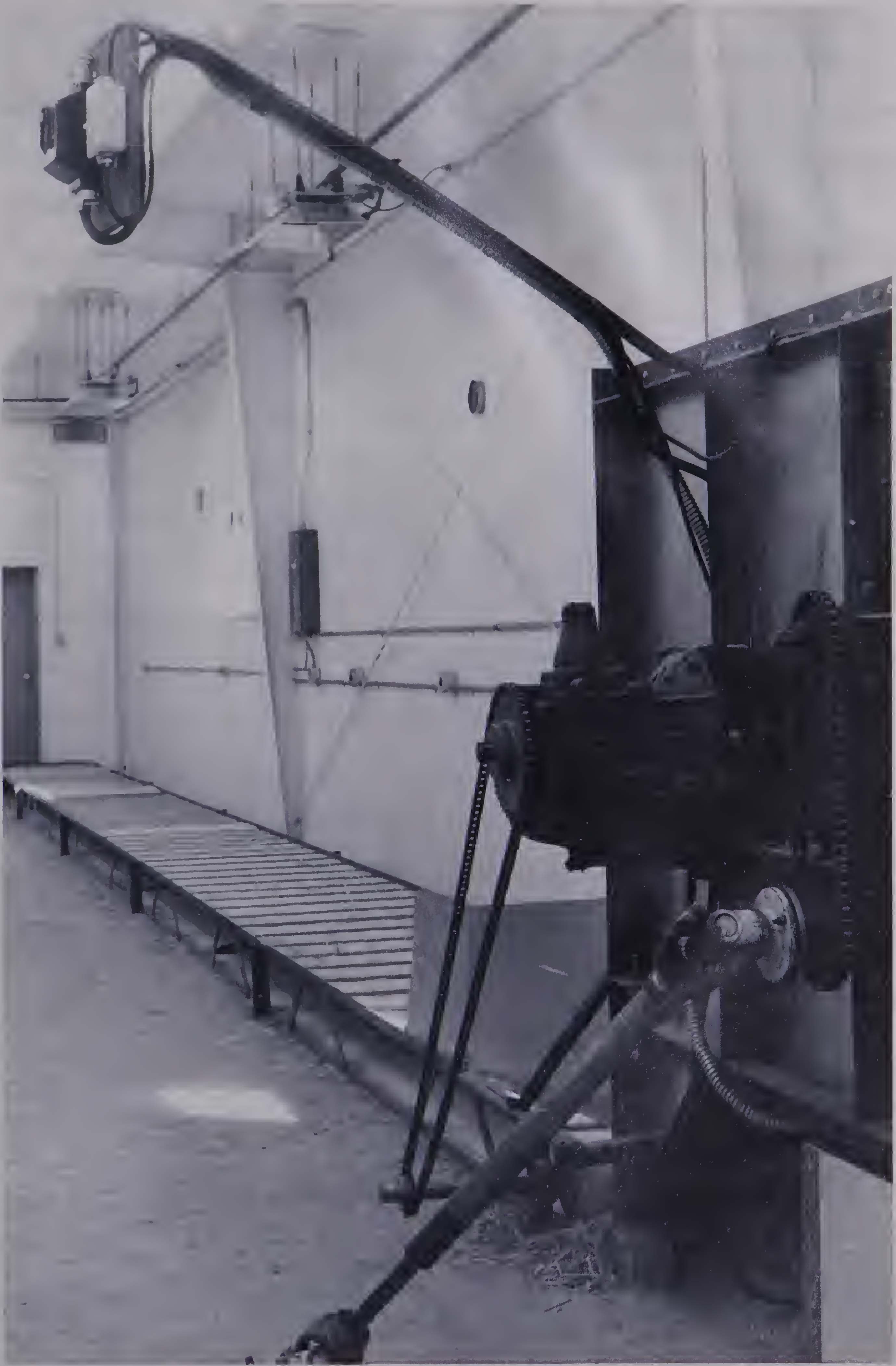

Figure 5: Canvas conveyor used to feed threshing unit.

3.2.4 Cleaning Screens

The samples collected from the threshing unit were cleaned using a series of three screens as shown in figure 6. The material first passed over an expanded metal screen (screen A in fig. 6) which was 21 in. wide and 26 in. long, having 3/8 in. by 7/8 in. openings. The screen was attached to an air vibrator which imparted a vibrating motion to the screen to aid in material movement. The screen pitch was 10°. The vibrator and screen assembly was secured to the frame of a commercial type seed cleaner, being positioned in such a way that all material falling through the openings in the expanded metal screen would be collected in the hopper of the seed cleaner. All material passing over the end of screen A (straw and unthreshed heads) was allowed to fall to the laboratory floor.

The material in the hopper was fed onto a 2 ft. square oscillating, round-hole screen (screen B, fig. 6) which was equipped with 4 brushes on the underside of the screen to aid in material separation and movement. The screen openings were 14/64 in. diameter. The grain and chaff falling through the screen openings were directed to a "Clipper" cleaner for final processing.

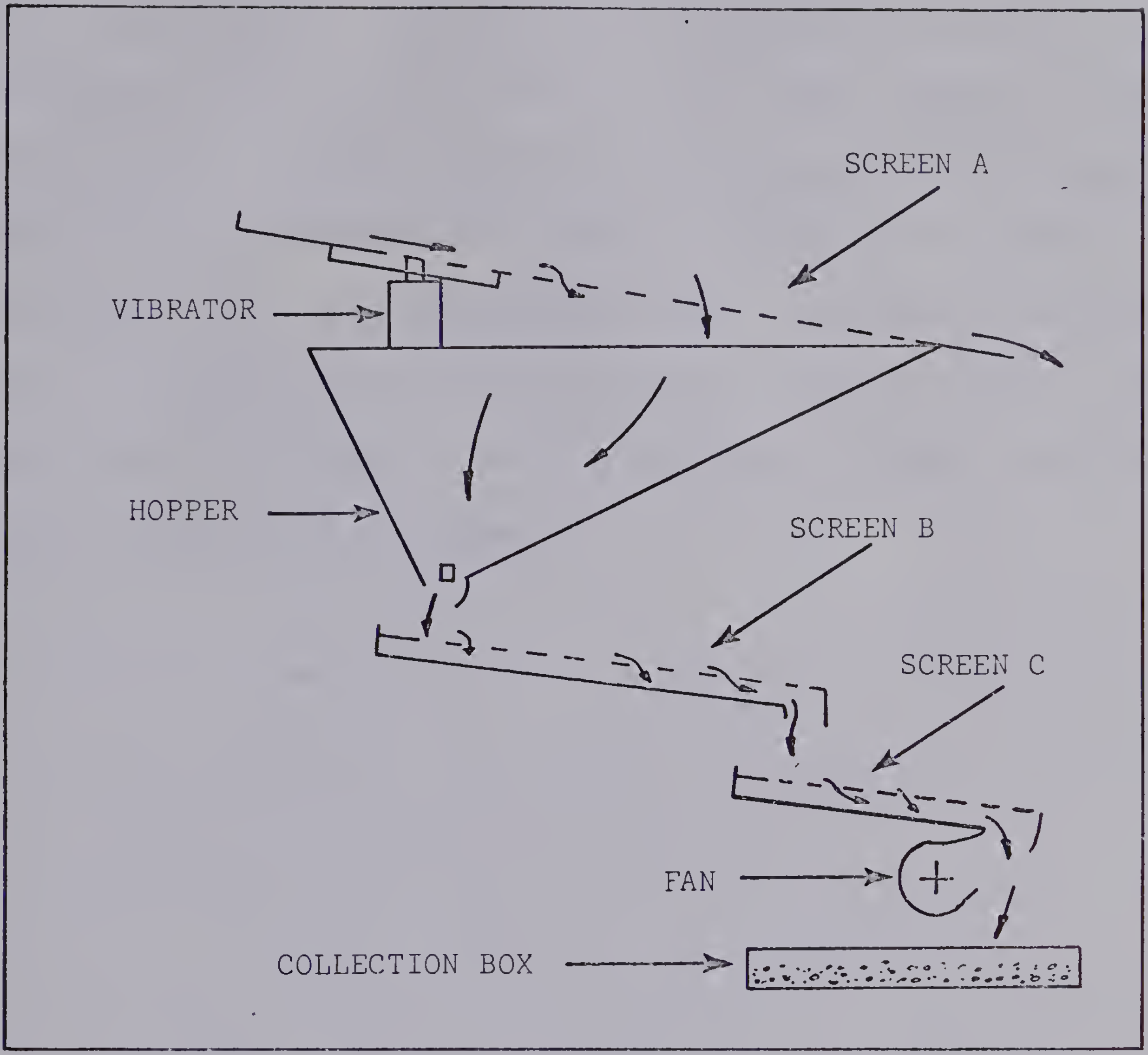

Figure 6: Schematic diagram showing the series of screens used in cleaning the grain samples.

The "Clipper" cleaner (figure 7) was fitted with a 9 in. wide and 15 in. long, round-hole screen (screen C figure 6) with hole openings of 16/64 in. diameter. The grain and chaff passing through the screen were directed through an air stream for final chaff removal. The fan speed was kept to a minimum and the air intake ports closed as much as possible to allow for some chaff removal, while still retaining a maximum portion of the fine kernel particles. The final clean grain sample was collected in the collection box as shown in figure 6. The effluent from the "Clipper" cleaner was checked at various intervals for the presence of grain fragments.

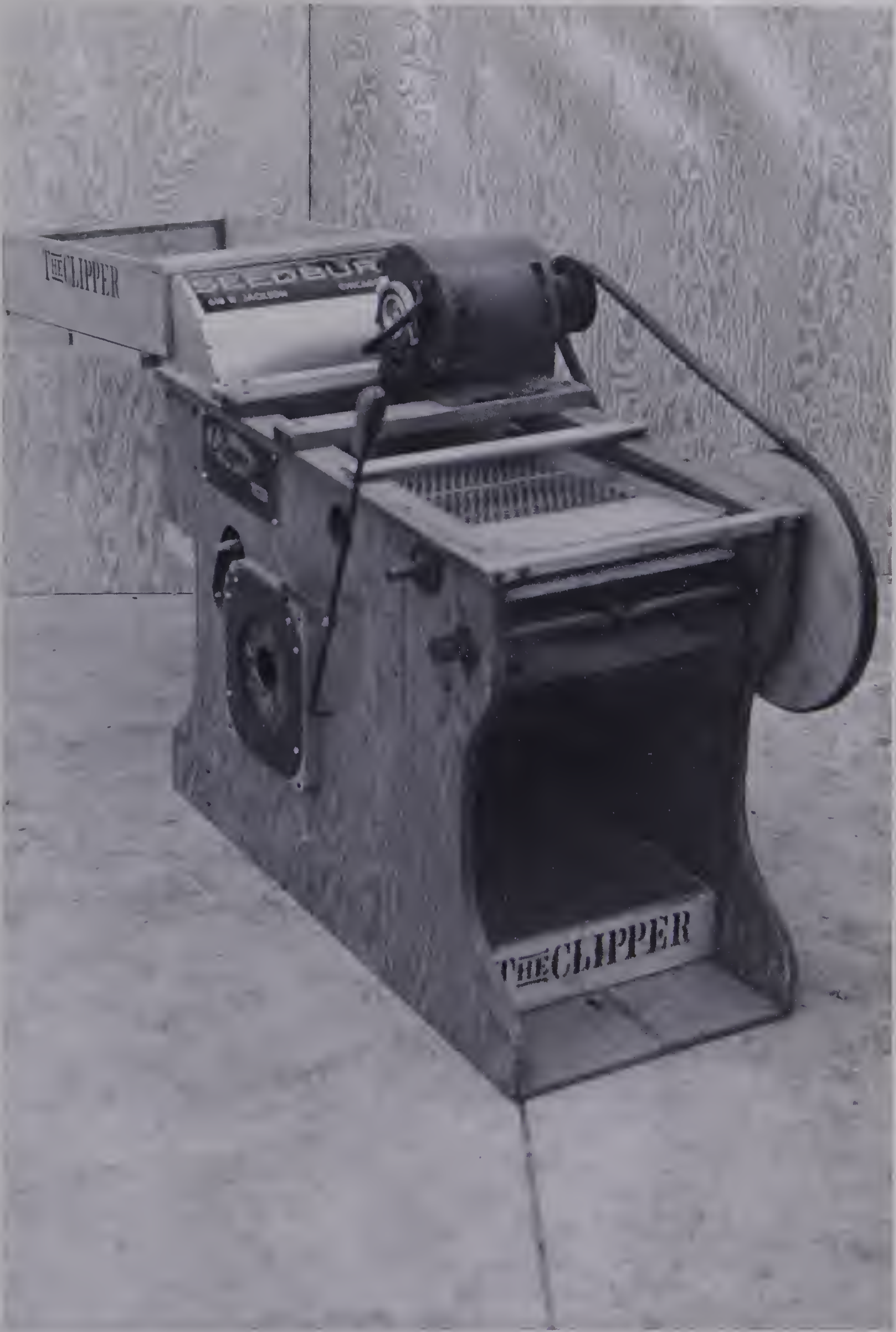

Figure 7: Clipper cleaner.

3.2.5 Conditioning Racks

Conditioning racks were built to hold the threshing material in the laboratory until it reached equilibrium moisture content. Two smaller racks on caster wheels, as shown in figure 8, and one larger stationary rack were set up. The smaller racks were 6.5 ft. long, 3.5 ft. wide and 6 ft. high having 5 shelves. The racks could be loaded from either side and the shelves were open to allow air movement between the layers of material.

3.2.6 Sample Divider

A conical type, gravity flow sample divider was used for sampling the free grain. The sample divider is shown in figure 9.

3.2.7 Air-Oven

A forced draft air-oven was used for grain moisture content determinations. The air-oven is shown in figure 10.

3.2.8 Vibrating Test Sieve Shaker

A vibrating sieve shaker, as shown in figure 11, was used in the assessment of mechanical grain damage. An 8 in. diameter standard wire mesh Tyler sieve was used. The sieve opening was .0937 in. The shaker was equipped with an automatic timer to permit a series of samples to be run for identical time periods. A rheostat and voltmeter combination was provided to assure identical vibratory conditions regardless of any variation in voltage supply.

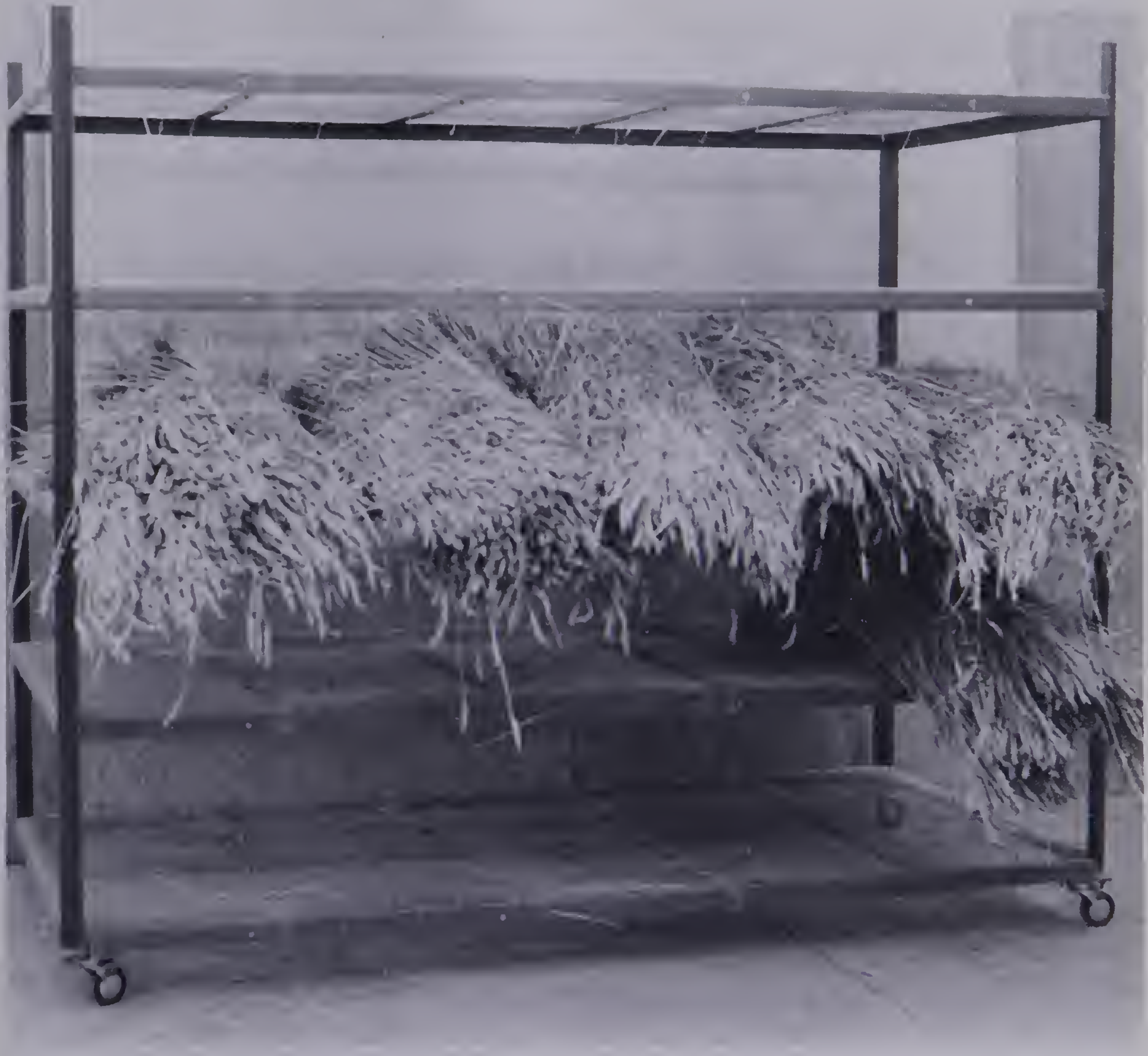

Figure 8: Conditioning rack.

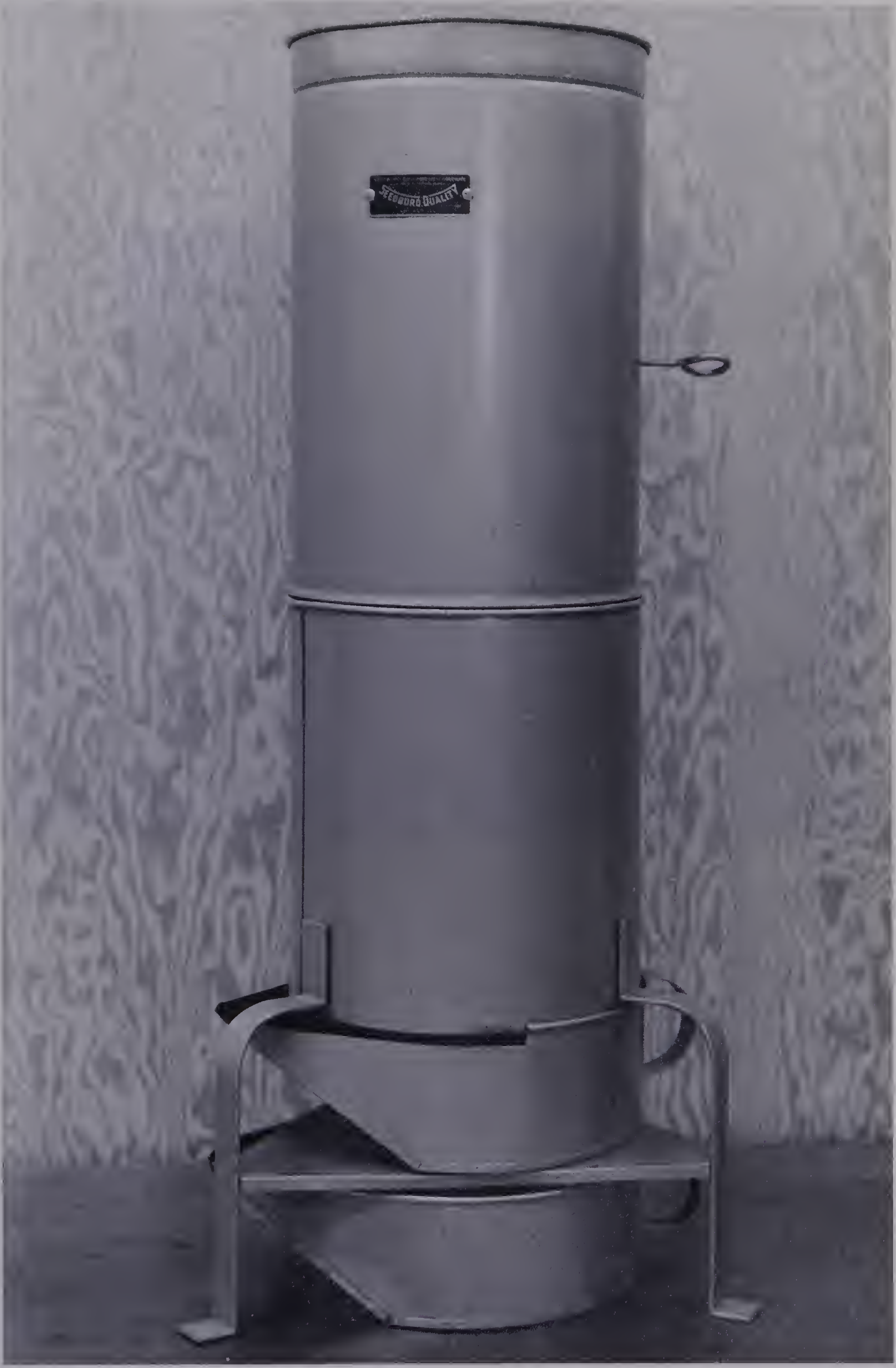

Figure 9: Sample divider.

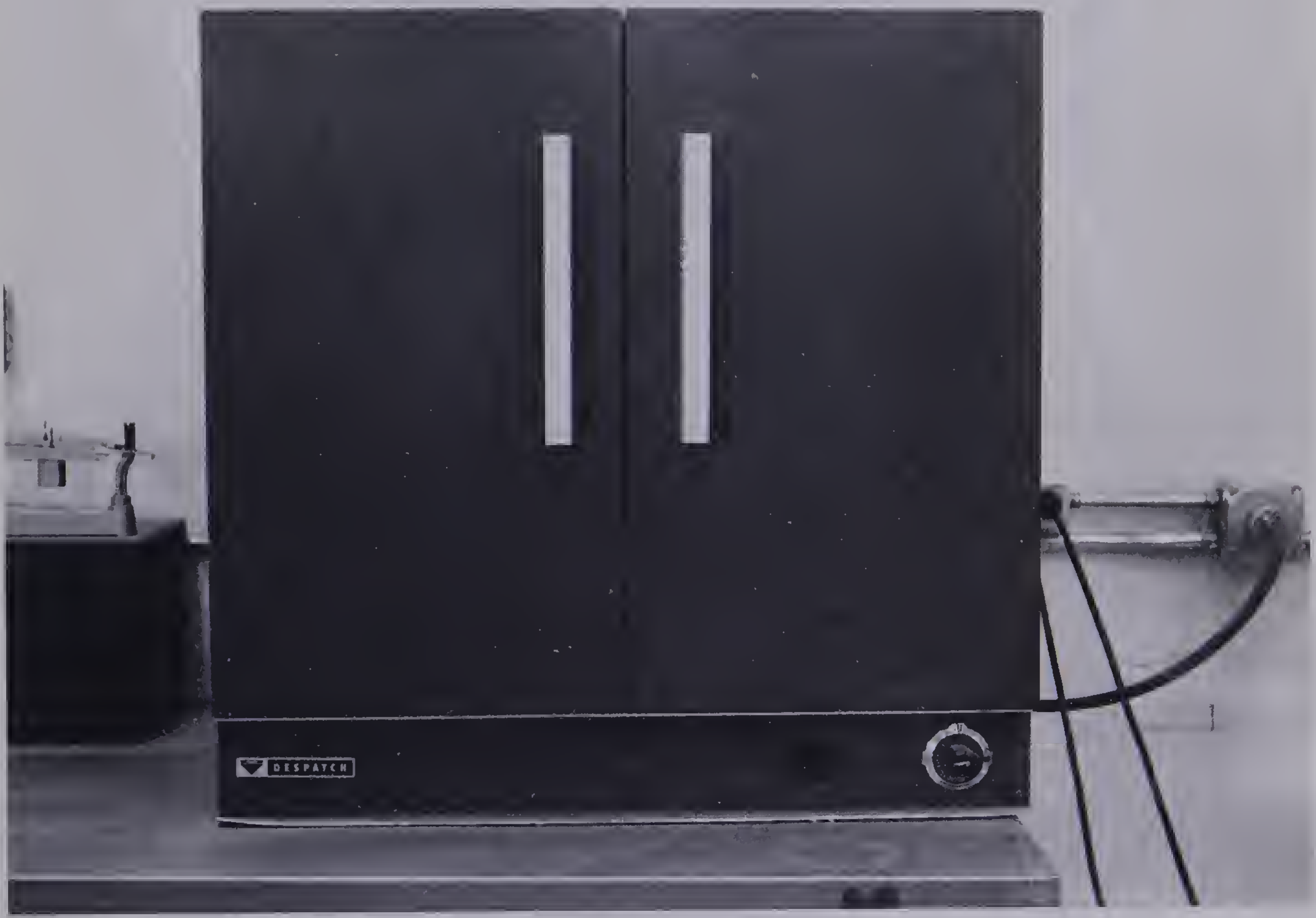

Figure 10: Air-oven.

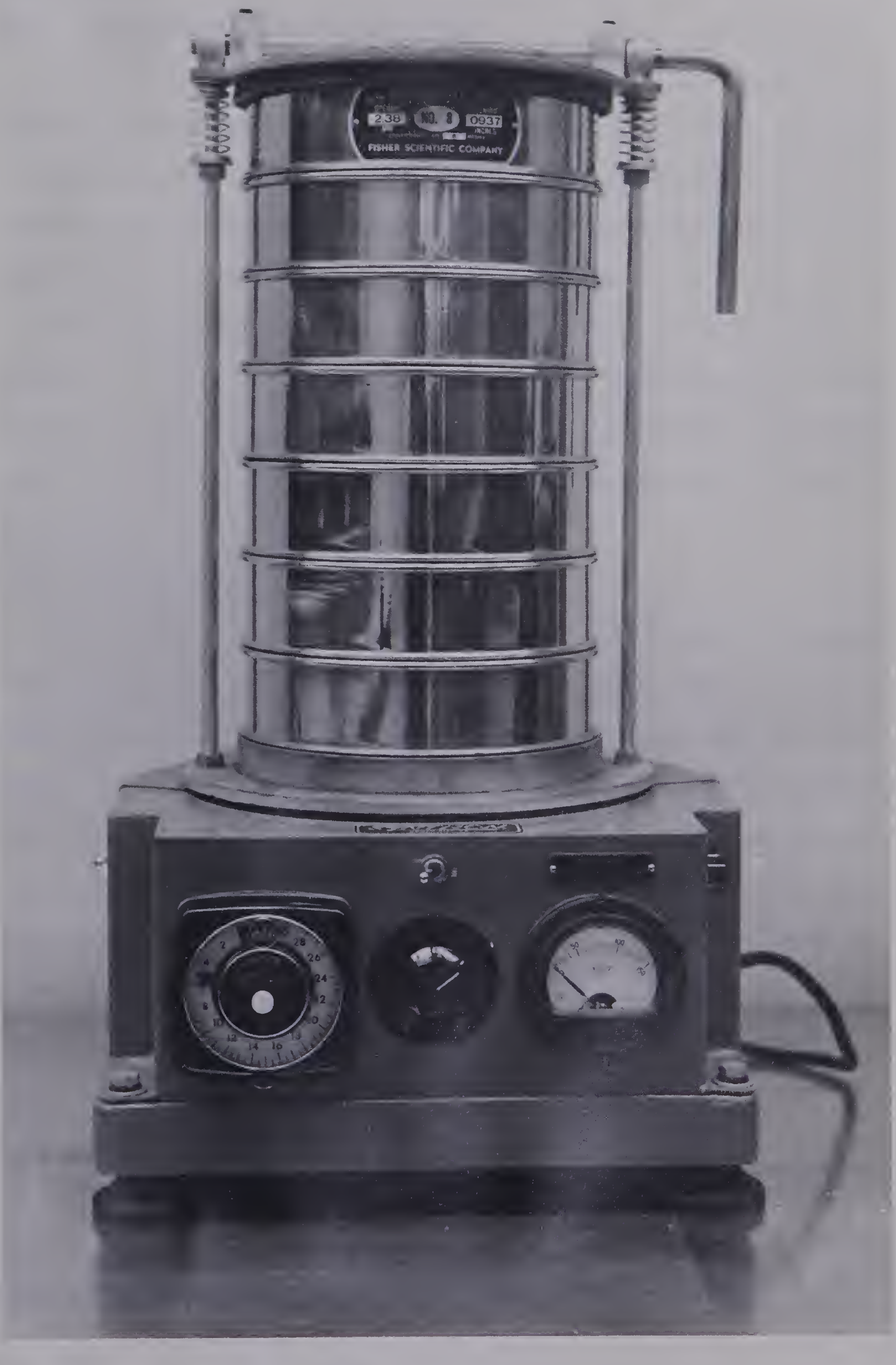

Figure 11: Test sieve shaker.

3.3 Methods

3.3.1 Sampling the Threshing Material

The wheat crop was cut from the field with a binder and the resulting sheaves hauled to the threshing site. The sheaves were stacked on wooden pallets and covered with polyethelene sheeting for protection from the weather until the experimental trials commenced. The resulting stack was 100 ft. long, 8 ft. wide and 6 ft. high.

For sampling purposes, the stack was divided into 10 ft. long sections. A random numbers table[41] was used to determine which of the 10 sections were sampled, with 20 sheaves being taken from each randomly selected section. The sheaves were always taken from the top layer of the stack.

3.3.2 Loading the Conditioning Racks

The sheaves selected from the stack were brought into the laboratory and placed on the shelves of the conditioning racks. Each of the two smaller racks held 50 sheaves and the larger stationary rack held 240 sheaves for a total of 340 sheaves. The racks were initially loaded and left for 5 days to enable the sheaves to reach an equilibrium moisture content in the laboratory, before being used for the experimental trials. Once the experiment was underway, sheaves were brought in as required, always making sure that they would be in the laboratory for at least 5 days before being used. Using this procedure, a relatively constant grain moisture content was assured for all trials.

3.3.3 Loading the Feed Conveyor

According to Csukás[18] and Arnold[3], heads first presentation of the crop to the cylinder was the most desirable method in terms of cylinder power requirements and threshing efficiency. Cooper and Neal[17], in

testing the attitude and method of laying the crop on the feed conveyor in the laboratory, decided a heads first arrangement with the heads up best simulated the desirable properties of a good swath in the field. Thus, the crop was laid on the conveyor with heads first and heads up throughout the experiment.

Sheaves were taken from the conditioning racks and weighed until 100 lbs. of material was obtained. The resulting sheaves were spread on the 50 ft. conveyor length with the heads first and up. Thus, the heads were always resting on straw rather than on the canvas conveyor. In every case, the material was spread as uniformly as possible over the entire conveyor length.

3.3.4 Selection of Variable Settings

Since cylinder speed was considered at 5 levels, concave clearance at 3 levels and feed rate at 3 levels, there were 45 different treatment combinations as given in Appendix I. A treatment combination was selected at random using a random numbers table[41]. The order of execution of the trials is given in Appendix II, as determined from the random numbers table for each of the four replicates.

3.3.5 Setting the Threshing Unit

The values of the independent variables selected had to be set on the threshing unit. Following is a description of the manner in which each setting was made.

3.3.5.1 Concave Clearance

The 3 levels of concave clearance were 1/4 in., 1/2 in. and 3/4 in. To make the settings, square gauge bars of 1/4 in., 1/2 in. and 3/4 in steel were used. The gauge bar was placed between the cylinder beater bar and the front concave bar and the concave was moved up or down until

the cylinder beater bar just touched the square gauge bar.

The rear concave clearance was constant at 1/8 in. throughout the experiment. It was set in the same manner as the front clearance.

3.3.5.2 Feed Rate

The 3 levels of feed rate were 100 lbs./min., 200 lbs./min and 300 lbs./min. The feed rate was varied by changing the speed of the feed conveyor, while maintaining a uniform crop stream thickness. For 100 lbs./min the conveyor speed was 50 ft./min., for 200 lbs./min the conveyor speed was 100 ft./min. and for 300 lbs./min. the conveyor speed was 150 ft./min. The conveyor speed change was accomplished by changing the drive sprocket size.

3.3.5.3 Cylinder Speed

The cylinder speed was varied by changing the engine speed of the International Harvester 706 diesel tractor, which powered the cylinder from the power-take-off shaft. The required engine speed for a given cylinder speed, was initially arrived at by reading the cylinder shaft speed using a tachometer and noting the tractor engine speed on the tractor engine tachometer. The values arrived at for engine speed and cylinder speed are given in Table 1.

TABLE 1: CYLINDER SPEED CALIBRATION

Cylinder Speed RPM	Tractor Engine Speed RPM
800	1350
900	1500
1000	1650
1100	1800
1200	1950

After calibration, the cylinder speeds were set by adjusting the govenor of the tractor until the appropriate engine speed was obtained.

It was felt that the tractor engine would have adequate power to drive the cylinder even at the lowest engine speed of 1350 rpm. A review of the literature concerning combine cylinder power requirements[12,21,22,35] indicated the dependence of required power on feed rate, and even though mean cylinder power requirements were low, peak power requirements could be 3 or 4 times greater. Arnold[4] reported cylinder power requirements for the stationary threshing unit he used in his threshing experiments. For the 24 in. wide and 21 in. diameter rasp-bar cylinder used, the mean cylinder power requirement was 3 horsepower at a feed rate of approximately 300 lbs./min. The peak cylinder power requirement was 11 horsepower at the same feed rate. The Nebraska Tractor Tests[37] indicated the horsepower of the International Harvester 706 diesel tractor at an engine speed of 1372 rpm to be 47.15. This indicated ample power to drive the cylinder under all circumstances for this research. It should be noted that throughout the experiment there was never an indication of lack of power to drive the cylinder.

3.3.6 The Initial Run

Once the required settings were made; the cylinder was run up to speed, the straw-walkers and pan under the walkers were set in motion and then the threshing material was fed to the threshing unit by starting up the feed conveyor. After the material passed through the unit, the straw-walkers were left running for a short time to ensure that all the material was in the collection box. The material in the collection box was then cleaned using the cleaning screens as described in section 3.2.4. The resulting clean grain catch was weighed and the weight recorded.

The weights are given in Appendix III. A 5 lb. sample was taken from the bulk, using the sample divider described in section 3.2.6, and the sample placed in a labelled plastic bag. The sample was set aside for future use in grain moisture content determinations and grain damage analysis.

3.3.7 The Rethresh Run

The threshed material (excluding free grain and chaff) from the initial run was put back through the threshing unit again to determine the amount of grain unthreshed on initial treatment. The material from the back of the threshing unit, as well as all the unthreshed heads collected from the screening process, were taken around to the front of the threshing unit and piled on the cement floor. The threshing unit was started up and material forked onto the feed conveyor. All rethresh runs were made using the highest cylinder speed (1200 rpm) and the same concave clearance as used for the initial run. The material in the collection box was cleaned using the same procedure as for the initial run. The resulting clean grain was weighed and discarded. The weights of the rethresh samples are found in Appendix IV.

3.3.8 Moisture Determinations

At the end of each day's work moisture content determinations were carried out on the samples collected that day. This was done as a check to ensure that grain moisture content equilibrium had been reached and the moisture content was constant for all the trials.

Air-oven methods were used as outlined in the United States Department of Agriculture Research Report[24]. Samples of 100 gram whole kernels were used. The sample for each trial was taken, using the sample divider from the 5 lbs. of material collected during the day. The sample

was placed in a forced draft air-oven at 266°F for 20 hours. The loss in weight was expressed as a percentage of the total sample weight, to give the grain moisture content on a wet basis. The grain moisture contents for each run are given in Appendix V.

3.3.9 Threshability Calculations

Threshability was calculated as a percentage using the following formula:

$$Y_T = \text{Threshability} = \frac{W_1}{W_1 + W_2} \times 100$$

W_1 = weight of initial grain catch (lbs.)

W_2 = weight of rethresh grain catch (lbs.)

$W_1 + W_2$ = total grain catch (lbs.)

The threshability values obtained appear in Appendix VI.

3.3.10 Mechanical Kernel Damage

On completion of the threshing trials, damaged kernel analyses were carried out on the samples, using the same random number order used for the threshing trials (Appendix II).

100 gram samples were taken using the sample divider from the 5 lb. bulk samples previously collected in the plastic bags. The samples so obtained were placed in the vibrating test sieve shaker for a period of 15 minutes. Two fractions resulted. The one fraction consisted of fine kernel fragments and shrunken kernels which passed through the No. 8 Tyler sieve used. The other fraction consisted of whole undamaged kernels, as well as half kernels and the whole kernels that were chipped or cracked and did not pass through the sieve openings. The two fractions were then hand-sorted to obtain a final measure of kernel damage. The shrunken, undamaged kernels passing through the sieve were removed by hand from the fraction. The fraction that did not pass through the sieve

was then carefully analyzed. Each kernel was visually inspected and any cracked or chipped kernels as well as half kernels were removed and bulked with the other damaged fraction. The total damaged kernels were weighed and the weight recorded. The weight of damaged kernels so obtained, was expressed as a percentage of the total 100 gram sample weight to give the percentage of kernels that were mechanically damaged, as determined by visual analysis. The resulting damage percentages are given in Appendix VII.

4. ANALYSIS AND RESULTS

The analysis consisted of statistical procedures involving analysis of variance and multiple regression. To obtain practical significance from the analysis, the resulting regression equations were used to obtain an expression for grain loss which was analyzed for a minimum value using partial derivatives.

4.1 Statistical Methods

For the analysis, threshability values found in Appendix VI, and mechanical grain damage values as found in Appendix VII were used. Grain moisture content and grain-to-straw ratio were considered to be constant for the analysis. Analysis of variance techniques were used to determine which of the factors* or factor interactions had a significant effect on threshability and grain damage. Multiple regression techniques were employed to arrive at a prediction equation for threshability and mechanical grain damage in terms of the measured variables. Calculations involved in the analysis of variance were made using a University of Alberta Computing Centre library program[23]. Calculation of the multiple regression involved a step-wise multiple regression program found in the I.B.M. Scientific Subroutine Package[28].

4.2 Analysis of Variance

The analysis of variance on the data was carried out on the basis of a randomized simple factorial design, with 4 replications of all treatment combinations. All variables were selected and the levels were fixed throughout the experiment thus indicating a fixed model[11,41]. The model for the analysis of variance was:

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* Factors refer to threshing parameters.

$$Y_{ijkr} = \mu + S_i + C_j + SC_{ij} + F_k + SF_{ik} + CF_{jk} + CSF_{ijk} + e_{ijkr}$$

where Y_{ijkr} is the r^{th} observation on the k^{th} feed rate on the j^{th} concave clearance on the i^{th} cylinder speed.

$i = 1,2, \ldots\ldots\ldots 5.$

$j = 1,2,3.$

$k = 1,2,3.$

$r = 1,2,3,4.$

Tests of significance for all main factors and factor interactions were carried out by comparing the mean square of the factor to be tested, with the error mean square using the appropriate degrees of freedom[41].

4.2.1 Analysis of Variance Results for Threshability

The analysis of variance for threshability is given in table 2. The mean threshability values for the five levels of cylinder speed, three levels of concave clearance, and three levels of feed rate, along with the grand mean, are tabulated in table 3.

The computed F-values in the analysis of variance table, indicated that main effects due to cylinder speed and concave clearance were highly significant*. The significance indicated that variations in threshability between the cylinder speeds and concave clearances considered were statistically significant. Over the range of feed rates considered,no statistically significant differences in threshability occurred.

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* Highly significant implies significance at the .01 probability level.

TABLE 2: ANALYSIS OF VARIANCE (THRESHABILITY).

Source of Variation	Degree of Freedom	Sum of Squares	Mean Squares	F
S = Cylinder Speed	4	88.130	22.030	158.5**
C = Concave Clearance	2	23.130	11.570	83.2**
SXC	8	10.200	1.270	9.1**
F = Feed Rate	2	0.024	0.012	<1
SXF	8	1.513	0.189	1.4
CXF	4	0.341	0.085	<1
SXCXF	16	0.611	0.038	<1
Error	135	18.770	0.139	
Total	179			

* Significant at .05 probability level.

** Significant at .01 probability level.

TABLE 3: MEAN THRESHABILITIES IN % FOR THE FACTORS.

Means For Cylinder Speeds

Level	Threshability
800 rpm	97.20
900 rpm	97.98
1000 rpm	98.62
1100 rpm	98.89
1200 rpm	99.14

Means For Concave Clearances

Level	Threshability
1/4 in.	98.77
1/2 in.	98.43
3/4 in.	97.90

Means For Feed Rates

Level	Threshability
100 lbs./min.	98.37
200 lbs./min.	98.38
300 lbs./min.	98.35

Grand Mean Threshability - 98.37%

The cylinder speed x concave clearance interaction (SXC) showed high statistical significance. The significant interaction indicated that differences in threshability between cylinder speeds depended on the concave clearance level, where responses were measured over all levels of feed rate.

The graphical illustration of the interaction as shown in figure 12, indicated the differential response of threshability to cylinder speed depending on the concave clearance level. For all cylinder speed levels, threshability was highest at the smallest concave clearance of 1/4 in. and lowest at the largest concave clearance of 3/4 in. with 1/2 in. clearance showing intermediate response.

From the mean threshability values in table 3, graphs were drawn with threshability being plotted against cylinder speed and concave clearance. The appropriate graphs appear in figure 13 and figure 14, respectively. Figure 13 indicated the resulting increase in percent threshability with an increase in cylinder speed. Threshability increased from 97.20% at 800 rpm cylinder speed, to 99.14% at 1200 rpm cylinder speed. From the graph in figure 14 an increase in concave clearance from 1/4 in. to 3/4 in. decreased the percentage threshed from 98.77% to 97.90%. The mean values for the feed rate levels given in table 3 indicated the negligible influence of variation in feed rate on threshability over the range considered.

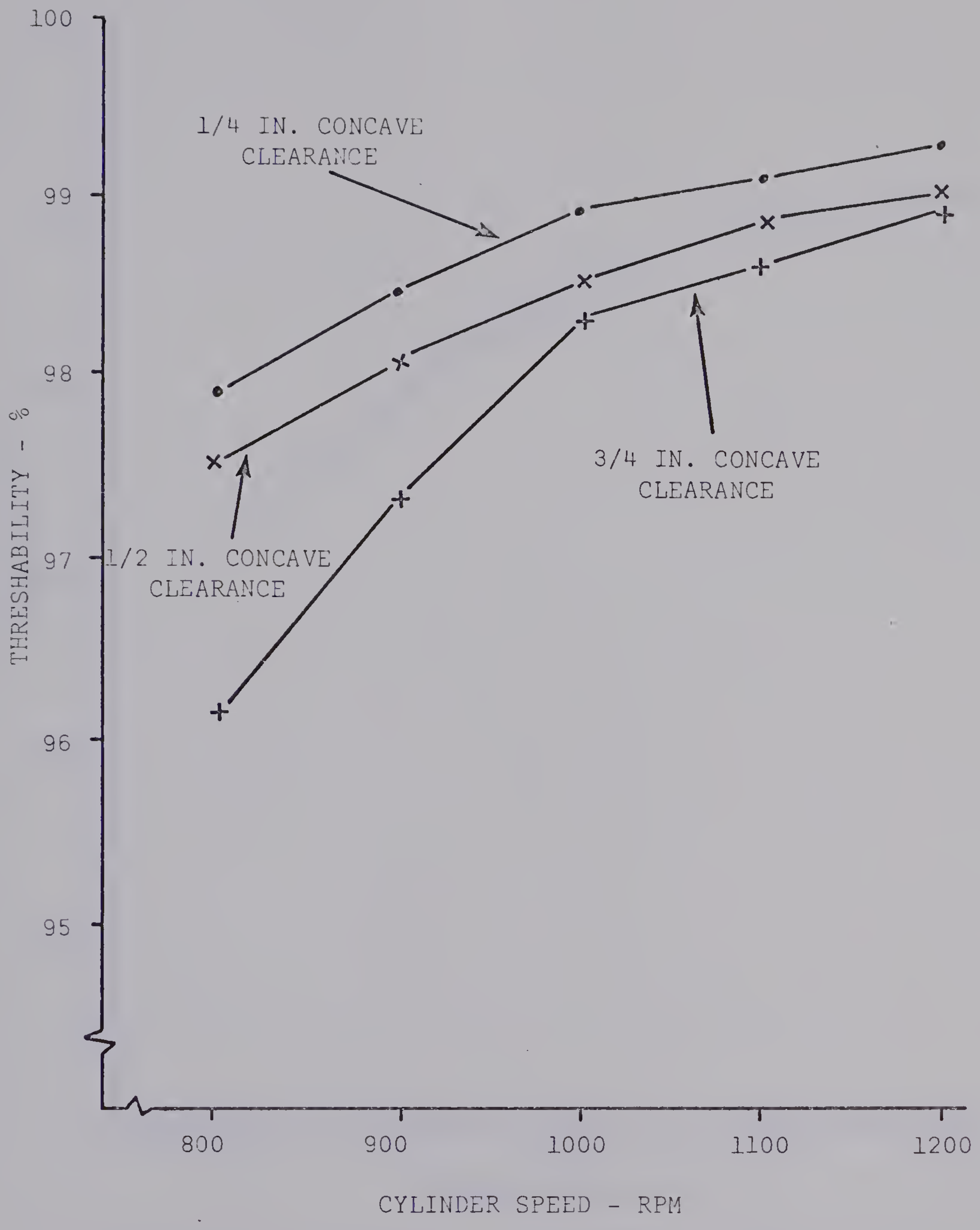

Figure 12: Graph illustrating cylinder speed and concave clearance interaction (threshability).

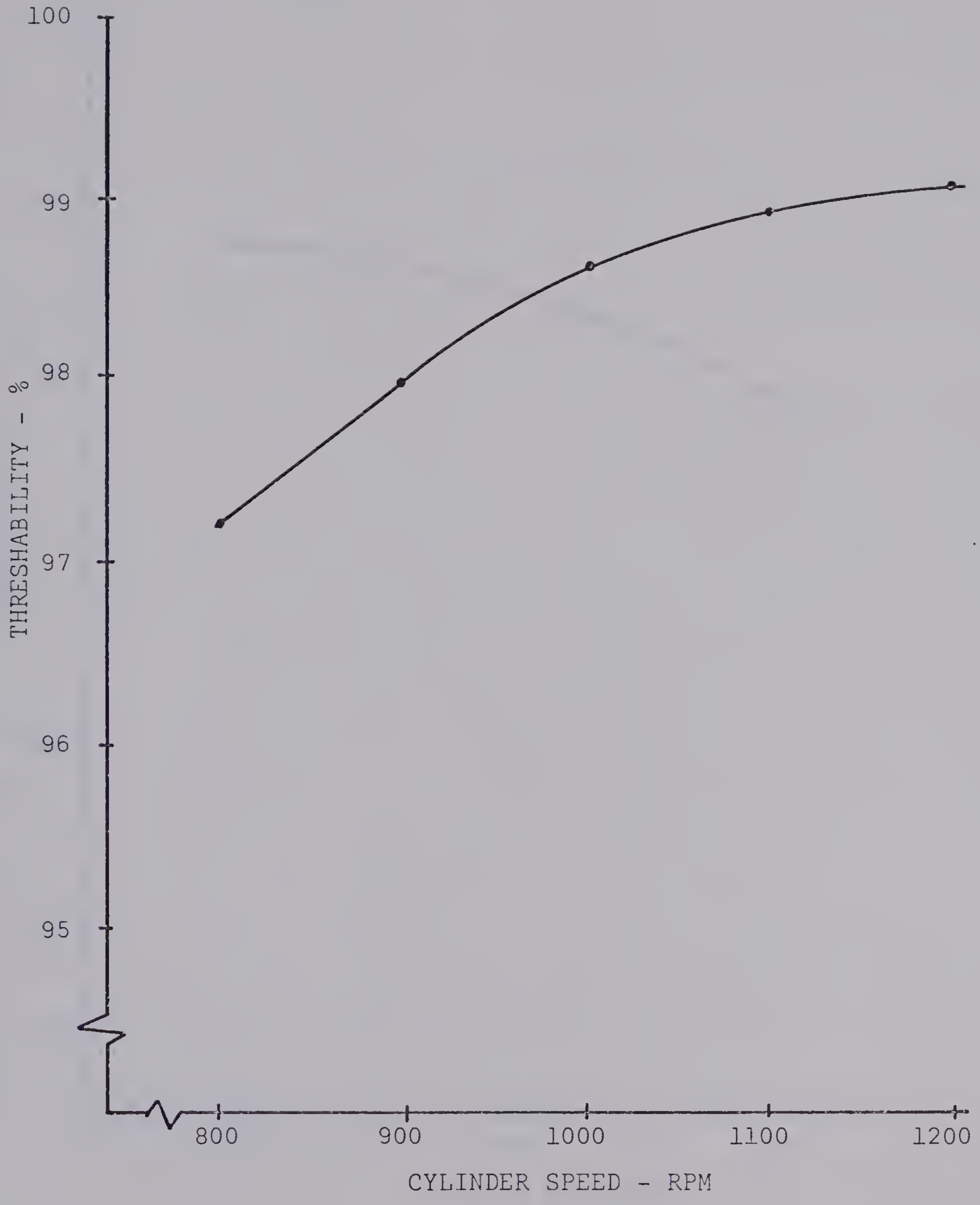

Figure 13: Graph illustrating effect of cylinder speed on threshability.

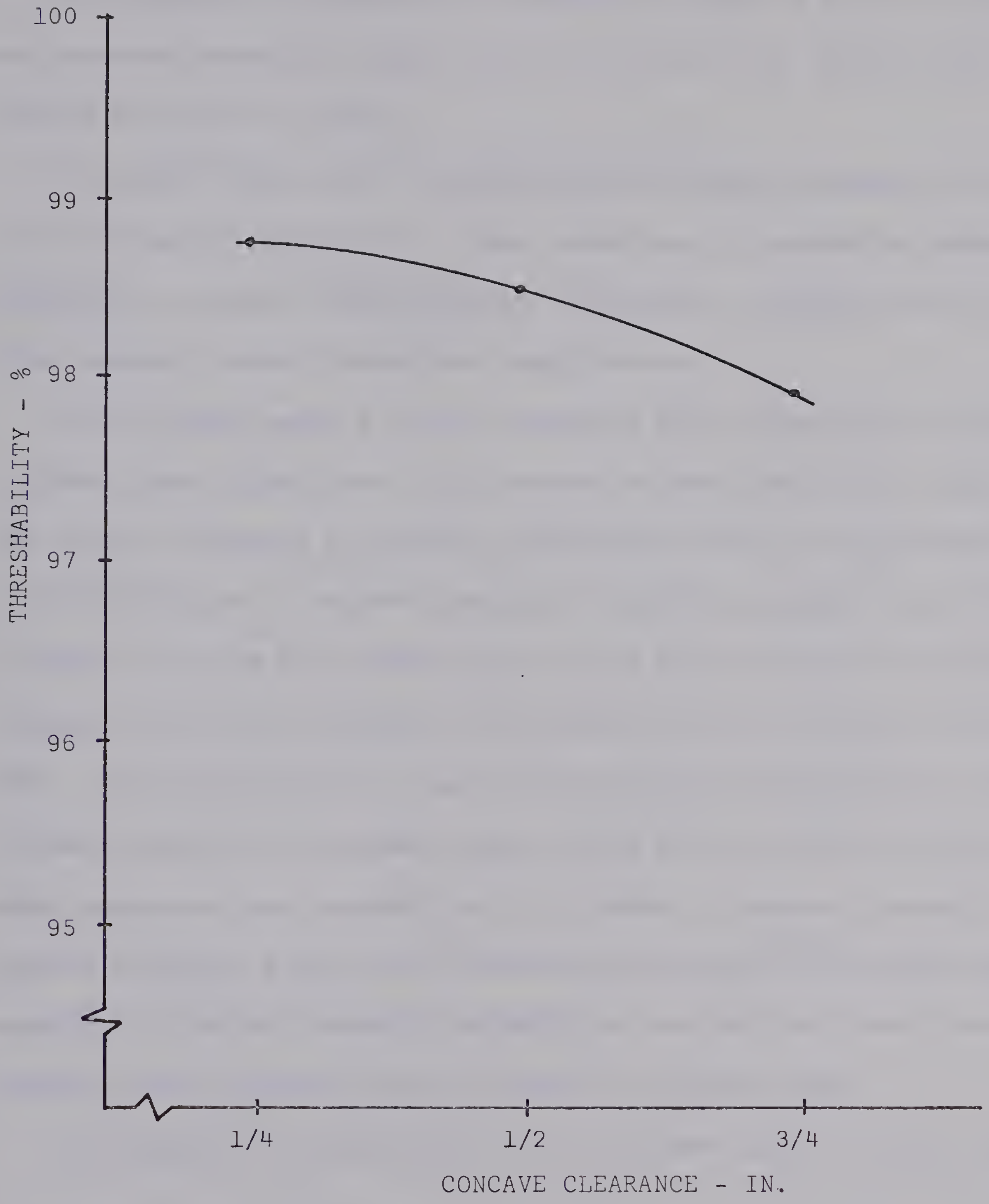

Figure 14: Graph illustrating effect of concave clearance on threshability.

4.2.2 Analysis of Variance Results for Mechanical Damage

The analysis of variance for mechanical damage is given in table 4 and the mean mechanical damage values for each of the levels of the factors are given in table 5.

The main effects due to cylinder speed, concave clearance and feed rate were highly significant. Thus, variations in mechanical damage between the cylinder speeds, between the concave clearances and the feed rates applied, showed statistical significance.

The cylinder speed x concave clearance (SXC) interaction and the cylinder speed x feed rate (SXF) interaction were both highly significant. The concave clearance x feed rate interaction (CXF) was significant*. The cylinder speed x concave clearance interaction implied that differences in damage response to cylinder speed varied with the level of concave clearance, where the responses were measured over all levels of feed rate. The cylinder speed x feed rate interaction indicated that differences in damage response to cylinder speed varied with the level of feed rate, where responses were measured over all levels of concave clearance. The concave clearance x feed rate interaction indicated differential damage response to concave clearance depending on the feed rate level, where all responses were measured over all levels of cylinder speed.

The graphical illustrations of the cylinder speed x concave clearance,

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* Significant implies significance at the .05 probability level.

TABLE 4: ANALYSIS OF VARIANCE (MECHANICAL DAMAGE).

Source of Variation	Degree of Freedom	Sum of Squares	Mean Squares	F
S = Cylinder Speed	4	2063.800	515.950	1943.2**
C = Concave Clearance	2	153.730	76.870	290.0**
SXC	8	22.617	2.827	10.7**
F = Feed Rate	2	33.939	16.969	64.0**
SXF	8	13.537	1.692	6.4**
CXF	4	2.673	0.668	2.5*
SXCXF	16	4.998	0.312	1.2
Error	135	35.725	0.265	
Total	179			

* Significant at .05 probability level.

** Significant at .01 probability level.

TABLE 5: MEAN KERNEL DAMAGE IN % FOR THE FACTORS.

Means For Cylinder Speeds

Level	Damage
800 rpm	2.9
900 rpm	3.8
1000 rpm	5.6
1100 rpm	8.0
1200 rpm	12.4

Means For Concave Clearances

Level	Damage
1/4 in.	7.7
1/2 in.	6.6
3/4 in.	5.4

Means For Feed Rates

Level	Damage
100 lbs./min	7.1
200 lbs./min	6.5
300 lbs./min	6.0

Grand Mean Damage - 6.5%

cylinder speed x feed rate and concave clearance x feed rate interactions are shown in figures 15, 16 and 17, respectively, Figure 15 indicated that damage was highest at 1/4 in. concave clearance for all levels of cylinder speed, with 1/2 in. clearance showing an intermediate effect and 3/4 in. concave clearance showing least damage. Figure 16 showed that damage was highest for the lowest feed rate (100 lbs./min) and decreased successively for 200 and 300 lbs./min. Damage was greatest at the highest cylinder speed for all levels of feed rate. From figure 17, mechanical damage was highest at the lowest feed rate and the smallest clearance and decreased with increasing feed rate and increasing concave clearance.

Graphs plotting mean mechanical damage against cylinder speed, concave clearance and feed rate appear in figures 18, 19 and 20, respectively. Increasing cylinder speed from 800 rpm to 1200 rpm increased mean damage from 2.9% to 12.4% as shown in figure 18. An increase in concave clearance from 1/4 in. to 3/4 in. caused damage to decrease from 7.7% to 5.4% as shown in figure 19. Finally, an increase in feed rate from 100 to 300 lbs./min., resulted in decreasing damage from 7.1% to 6.0% as shown in figure 20.

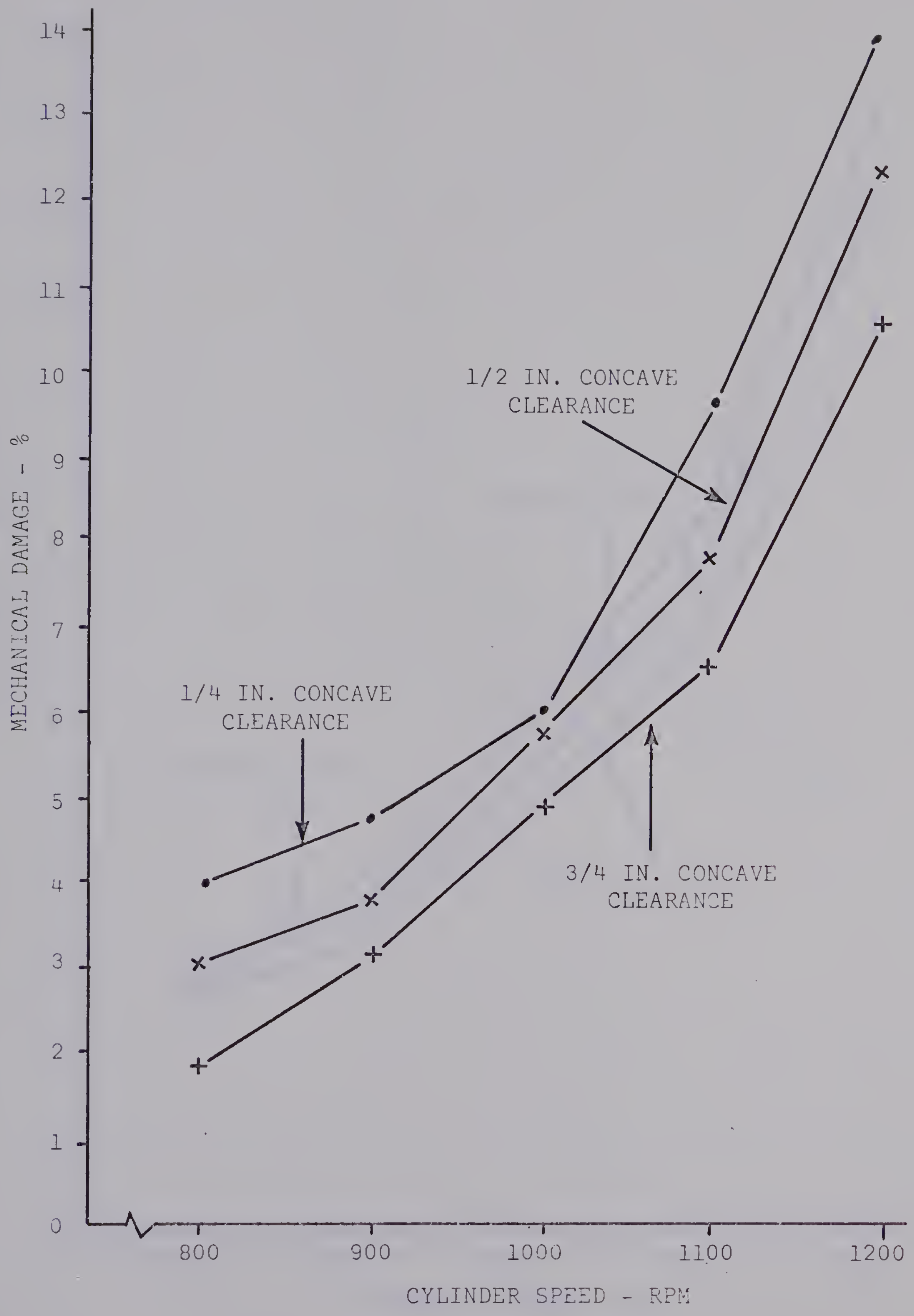

Figure 15: Graph illustrating cylinder speed and concave clearance interaction (mechanical damage).

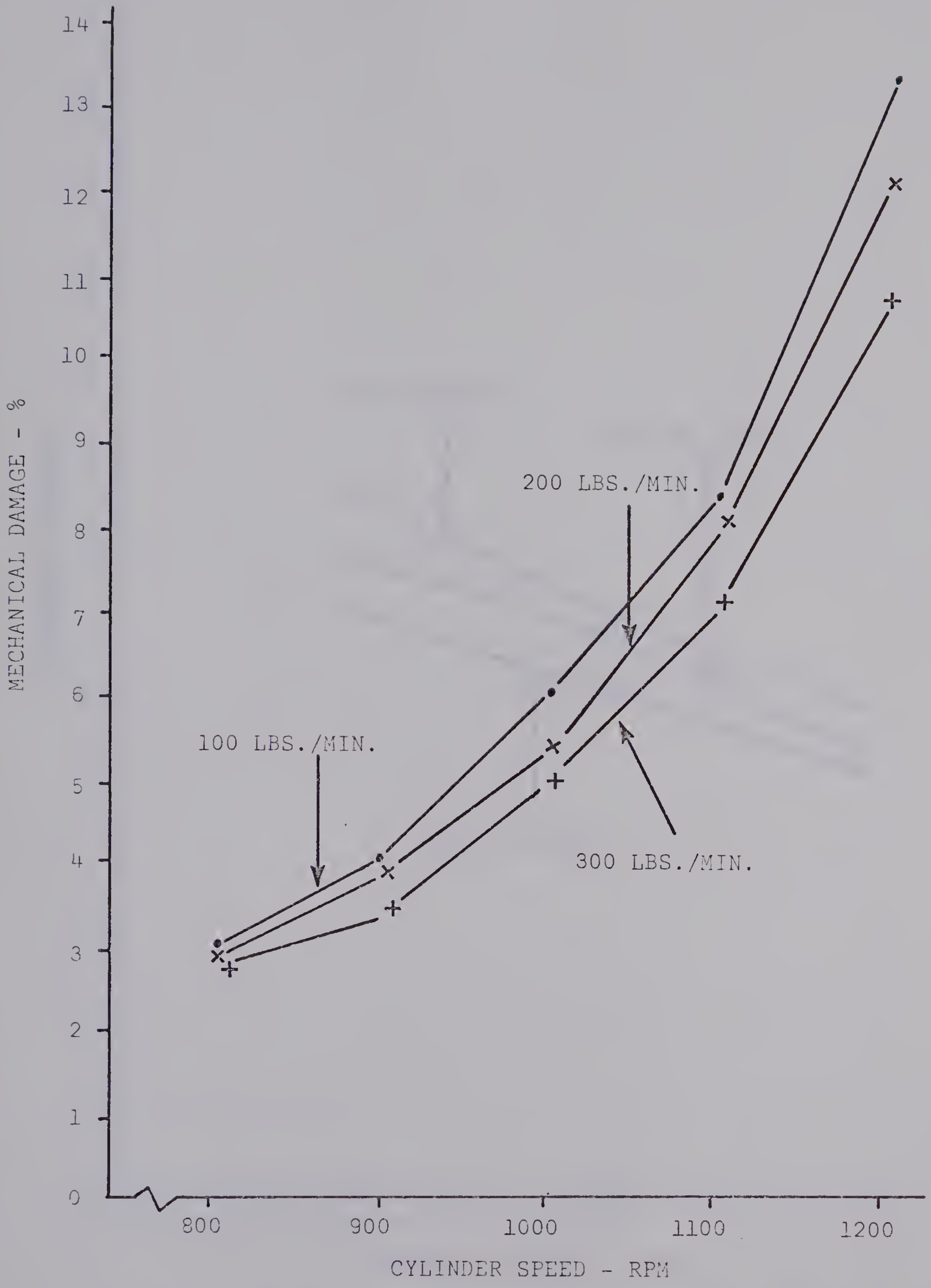

Figure 16: Graph illustrating cylinder speed and feed rate interaction (mechanical damage).

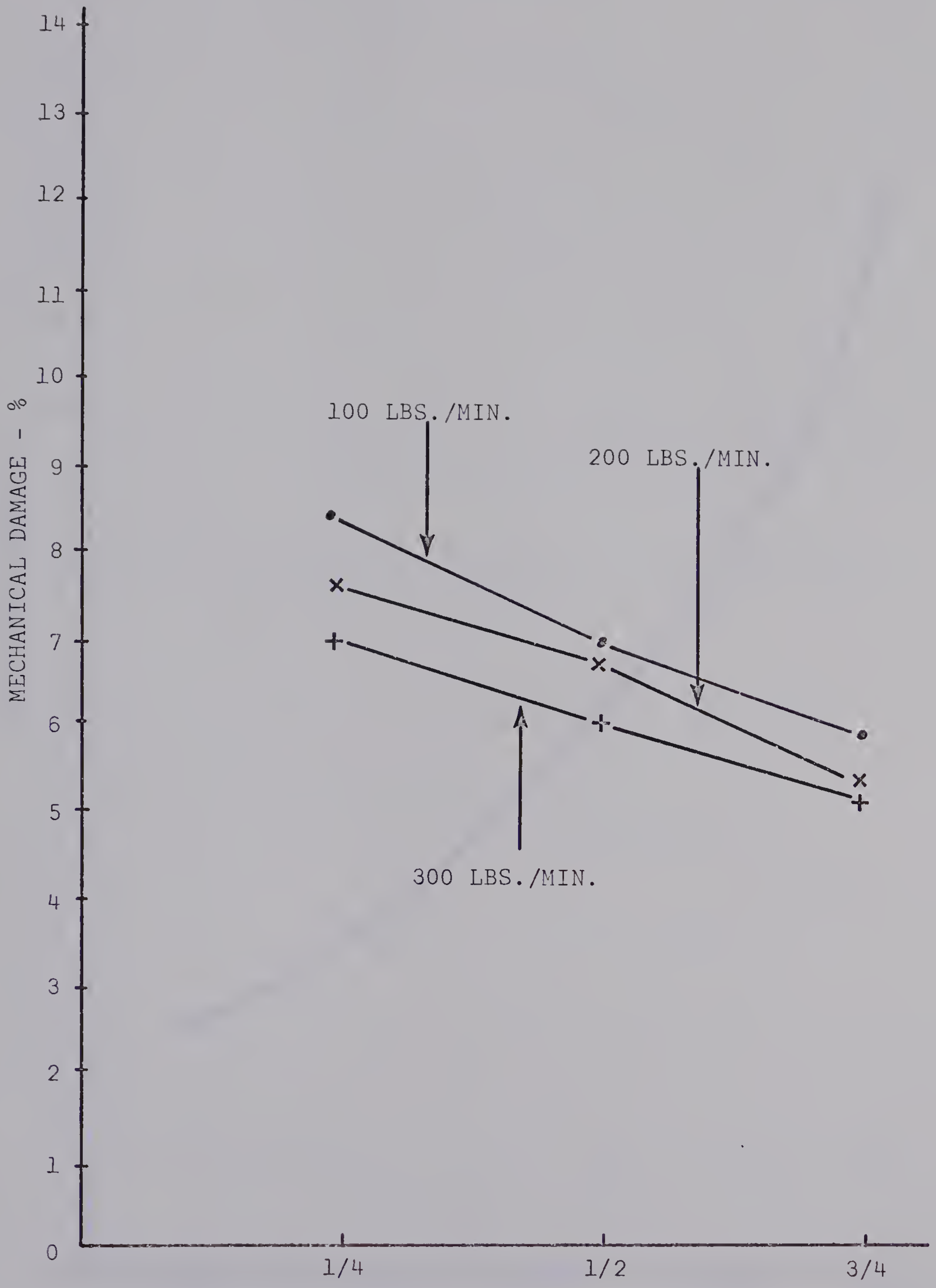

Figure 17: Graph illustrating concave clearance and feed rate interaction (mechanical damage).

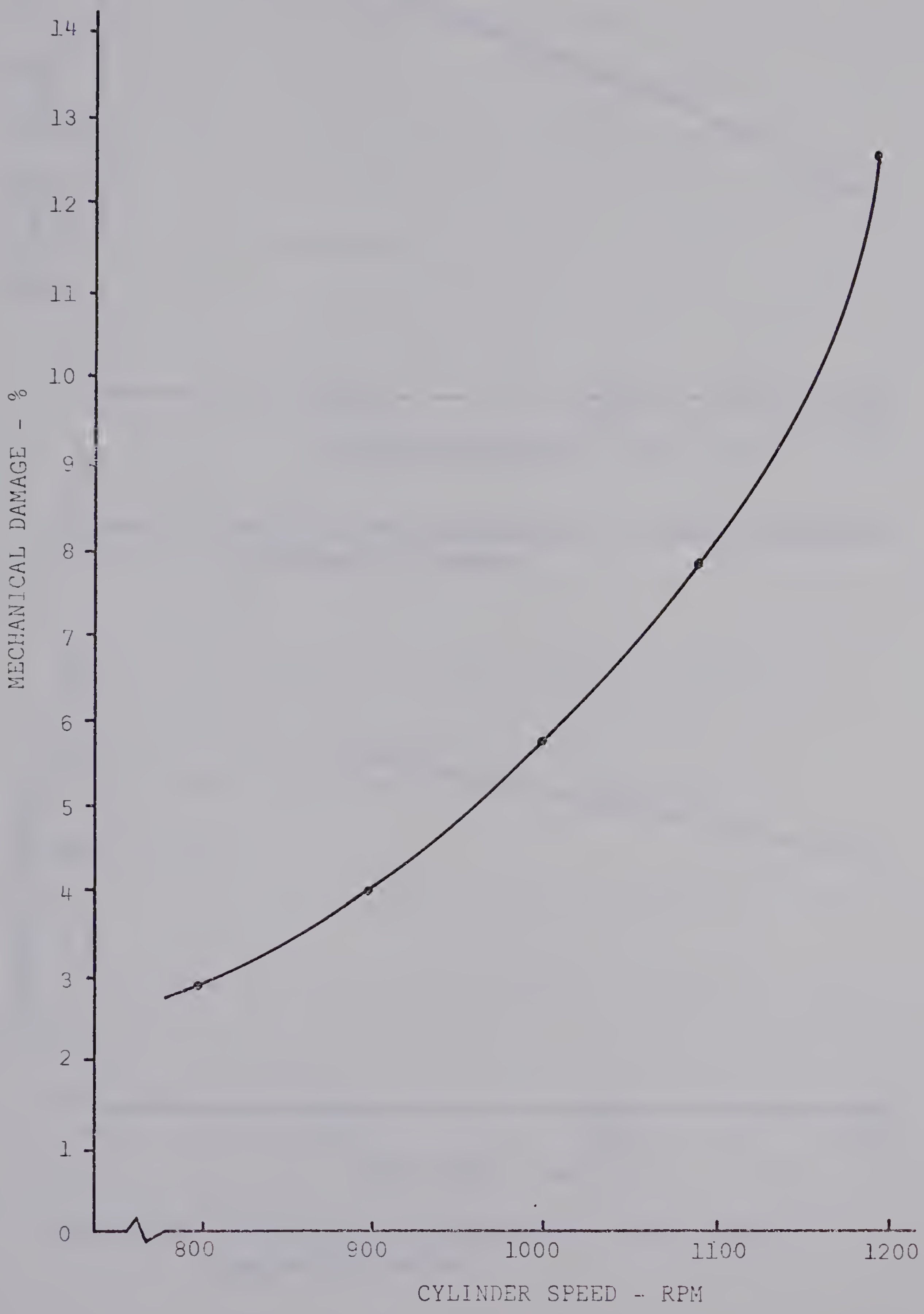

Figure 18: Graph illustrating the effect of cylinder speed on mechanical damage.

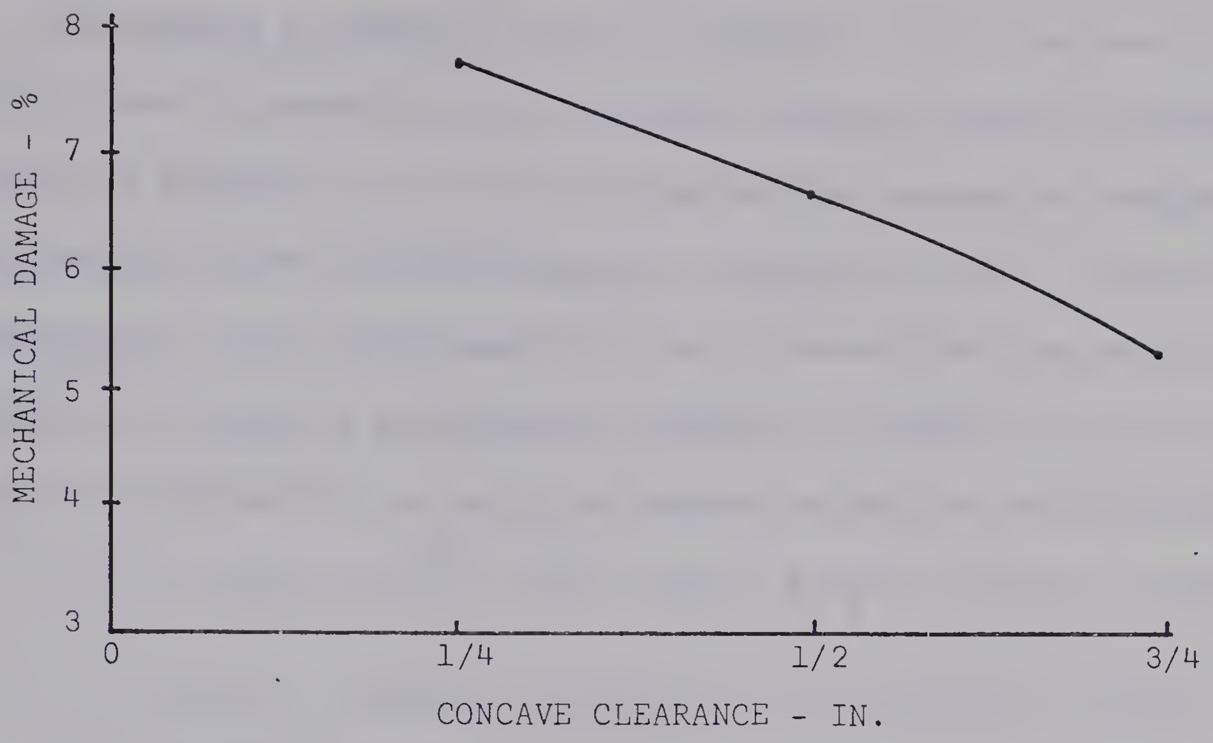

Figure 19: Graph illustrating effect of concave clearance on mechanical damage.

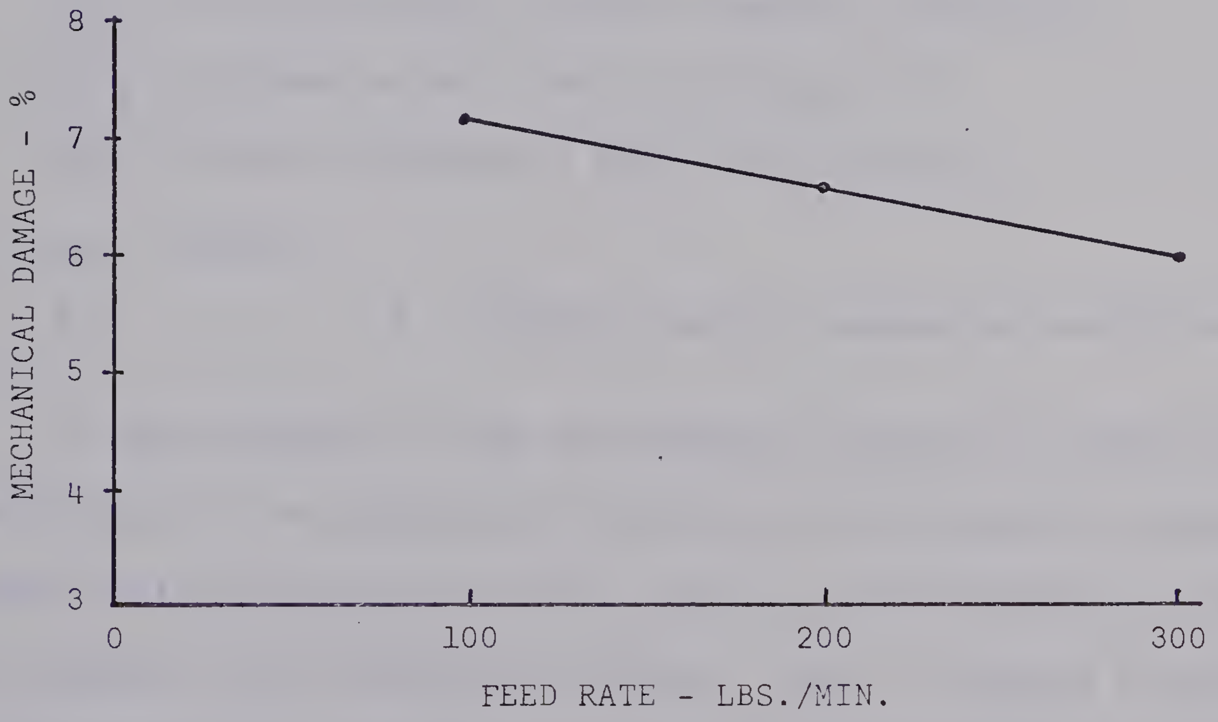

Figure 20: Graph illustrating effect of feed rate on mechanical damage.

4.3 Multiple Regression

The graphs in figures 13 and 14 indicated that there was a relationship between threshability and cylinder speed and concave clearance. Graphs in figures 18, 19 and 20 indicated that mechanical damage could be expressed in terms of the independent variables as well. The two-factor interaction terms could also be of use in describing threshability and mechanical damage in a regression equation. In view of this, the general model considered for the multiple regression had the following form:

$$Y = A_0 + A_1X_S + A_2X_s^2 + A_3X_C + A_4X_F + A_5X_SX_C + A_6X_SX_F + A_7X_CX_F.$$

Y = dependent variable (threshability or mechanical damage).

X_S = cylinder speed.

X_C = concave clearance.

X_F = feed rate.

X_SX_C = cylinder speed x concave clearance interaction.

X_SX_F = cylinder speed x feed rate interaction.

X_CX_F = concave clearance x feed rate interaction.

A_0 = constant.

$A_1, \ldots\ldots, A_7$ = multiple partial regression coefficients.

It was desirable to keep the regression equation as simple as possible but it was necessary to include all the important variables to obtain a high correlation and thus ensure a good relationship between the dependent and independent variables. Thus, a computer program[28] for stepwise multiple regression was used to determine the relationship. All of the independent variables given in the general model were made available to the program but only the independent variables which reduced the sum of squares by 1% or more were retained in the final multiple

regression equations.

4.3.1 Regression Equation for Threshability

The results of the regression analysis for threshability are given in table 6. The independent variables contributing to the regression equation using the criterion of a 1% reduction in sum of squares were cylinder speed, cylinder speed squared, concave clearance and cylinder speed x concave clearance interaction. The multiple correlation coefficient of 0.91 indicated a good relationship between percentage threshability and the independent variables selected. The cumulative proportion of the total sum of squares accounted for by the independent variables was 0.82. The standard error of estimate indicated that values of threshability could be estimated from values of the independent variable to within ± 0.38% using the regression coefficients obtained.

The analysis of variance for the regression indicated a highly significant F-value. The reduction in sum of squares due to the regression was significant at the .01 probability level.

TABLE 6: REGRESSION ANALYSIS RESULTS FOR THRESHABILITY

Analysis Of Variance For The Regression

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Attributable to Regression	4	117.570	29.393	204.1**
Deviation from Regression	175	25.187	0.144	
Total	179	142.757		

Regression Equation:

$$Y_T = 87.9010000 + 0.021689X_S - 0.000010X_S^2 - 8.549019X_C + 0.006806X_SX_C.$$

Multiple Correlation Coefficient = 0.91.

Cumulative Proportion of Sum of Squares Reduced = 0.82.

Standard Error of Estimate = 0.38%.

4.3.2 Regression Equation for Mechanical Damage

The results of the regression analysis for mechanical damage are given in table 7. The independent variables selected using the criterion of 1% reduction in sum of squares were cylinder speed, cylinder speed squared and cylinder speed x concave clearance interaction. The multiple correlation coefficient of 0.98 indicated a very good relationship between percentage mechanical damage and the independent variables selected. A good relationship was further indicated by the fact that 0.95 of the total sum of squares was accounted for by the independent variables. The standard error of estimate of ± 0.81% indicated the accuracy with which values of percentage mechanical damage could be estimated using the regression coefficients obtained for the regression equation.

The analysis of variance for the regression indicated that the reduction in sum of squares due to the regression was highly significant.

TABLE 7: REGRESSION ANALYSIS RESULTS FOR MECHANICAL DAMAGE.

Analysis Of Variance For The Regression

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Attributable to Regression	3	2218.250	737.083	1151.7**
Deviation from Regression	176	112.750	0.640	
Total	179	2331.000		

Regression Equation:

$$Y_D = 36.200000 - 0.082244X_S + 0.000054X_S^2 - 0.004576X_SX_C.$$

Multiple Correlation Coefficient = 0.98.

Cumulative Proportion of Sum of Squares Reduced = 0.95.

Standard Error of Estimate = 0.81%.

4.4 Analysis of Results for Optimization

One of the objectives of this research was to determine if some level of the threshing parameters considered would result in an optimum situation of high threshability and low kernel damage. Thus, the resulting multiple regression equations arrived at were used to determine a measure of total grain loss on the basis of the results obtained. The resulting expression for loss was analyzed for a minimum point using methods employing partial derivatives.

4.4.1 Total Grain Loss

Bainer, et al[7], discuss types and sources of seed loss from a combine. Damaged kernels do not represent a direct loss of yield except for the small fragments which are lost due to pneumatic separation. However, presence of cracked kernels may result in dockage when wheat is sold for milling purposes. Seed damage can also result in poor germination if the seed is considered for planting. Thus, seed damage is undesirable and generally can be considered as a loss. Unthreshed seed also represents grain loss. Kernels remaining in the ear and passing through the combine would represent a direct loss. Unthreshed heads which are retained for rethreshing often result in damaged kernels and could be considered as a loss. Thus, for the purposes of this analysis, total grain loss included the damaged kernels and the unthreshed grain.

The regression equation arrived at for mechanical damage (Y_D) gave an expression for the damaged kernels portion of total loss. The regression equation for threshability (Y_T) could be used to obtain the unthreshed portion. Since threshability was defined as the percentage by weight of the grain removed from the ears during initial threshing,

the unthreshed portion would be given by $100 - Y_T$. Total loss becomes:

$$Y_L = (100 - Y_T) + Y_D$$

where Y_L = total grain loss (%).

$100 - Y_T$ = unthreshed grain (%).

Y_D = damaged grain (%).

Summation of $(100 - Y_T)$ and Y_D gave Y_L in terms of the independent variables selected for the regression equations, that is,

$$Y_L = 48.299000 - 0.103933X_S + 0.000064X_S^2 + 8.549019X_C - 0.011382X_SX_C.$$

4.4.2 Minimum Grain Loss

To determine the minimum of Y_L, methods using partial derivatives were used as set out in Protter and Morrey[40]. The method involved taking the partial derivatives of Y_L with respect to X_S and X_C. The resulting derivatives were set equal to zero and the two equations solved simultaneously to arrive at a solution.

The partial derivative of Y_L with respect to X_S is:

$$-0.103933 + 0.000128X_S - 0.011382X_C. \quad \dots\dots\dots (1)$$

The partial derivative of Y_L with respect to X_C is:

$$8.549019 - 0.011382X_S. \quad \dots\dots\dots\dots\dots\dots (2)$$

By setting equation 1 and equation 2 equal to zero and solving simultaneously, it was found that

X_S = 751 rpm

X_C = .69 in.

The solution indicated that minimum grain loss would occur at a cylinder speed of 751 rpm and .69 in. concave clearance. In this investigation, cylinder speed was considered at levels of 800 to 1200 rpm. Thus, 751 rpm fell out of the range considered and indicated that the

optimum solution lies beyond the range of this experiment. Cylinder speed was not considered at a low enough level to obtain a minimization of grain loss. Since extrapolation of the regression equation beyond the values considered in the experiment was invalid, the solution was also invalid. However, the procedure was useful in that it indicated future experiments should consider lower cylinder speeds if minimization of grain loss is to be considered.

5. DISCUSSION OF RESULTS

5.1. Threshability and Grain Damage

High cylinder speeds and small concave clearances resulted in increased threshability and increased mechanical damage (tables 3 and 5). According to Arnold[3], an ear of grain is subject to large impulsive forces at high cylinder speeds. Also, at the higher cylinder speeds, the ear may be subject to a greater number of impacts than at the lower cylinder speeds. Decreasing concave clearance may have:

1. increased the chance of an ear of grain being struck by the cylinder beater bar, and
2. increased the chance of multiple impacts to the ear before it passed from the threshing area.

It is convenient to describe the above factors as an "impact model". Thus, the impact model may account for the increased threshability and kernel damage with increased cylinder speed and decreased concave clearance.

An increase in feed rate resulted in a decrease in mechanical damage as indicated in table 5. This might be due to a "cushioning"[7] effect at the higher feed rates, that is, the crop stream between the cylinder and concave may have been denser at the higher feed rates, thus providing a cushion for the ears of grain. The cushioning effect would fit the impact model. However, from tables 2 and 3, changes in feed rate had no significant effect on threshability. The cushioning effect which may have decreased damage at the high feed rates, should also have decreased threshability at the high feed rates. Since this was not supported by the results, a "frictional model" may be indicated, that is, increased feed rate may have increased the crop

stream density which in turn increased the frictional forces* between particles in the crop stream. Thus, the cushioning effect of the impact model may have tended to decrease threshability but was offset by the increased rubbing action of the frictional model. The net result could be little or no change in threshability. The rubbing effect of the frictional model would not likely result in damaged kernels[26].

Thus, the effects of cylinder speed, concave clearance and feed rate on threshability and kernel damage may be described on the basis of an "impact-friction" model. The model fit's the results obtained in the experiment.

From table 2 and table 4, the large F-value for cylinder speed relative to the F-values for the other parameters, indicated that it was of prime importance in causing variations in threshability and mechanical kernel damage in this study. The importance of cylinder speed as a mechanical threshing parameter is supported by findings of other researchers[3,9,10].

As shown by the graph in figure 12, the differences in threshability between 1/2 in. concave clearance and 3/4 in. concave clearance were greater than the differences between 1/2 in. concave clearance and 1/4 in. concave clearance, especially at the lower cylinder speeds.

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* Frictional forces refer to the forces caused by the relative motion of the material within the crop stream.

However, for all levels of cylinder speed, threshability was highest at the smallest concave clearance and lowest at the largest concave clearance. The differential response of threshability to cylinder speed, depending on the concave clearance used, was evidenced by the significant F-value for the cylinder speed x concave clearance interaction in table 2.

From figure 15, percentage mechanical damage differences between the concave clearance levels increased as the cylinder speed increased from 1000 rpm to 1200 rpm. From 800 to 1000 rpm the differences decreased. This resulted in a significant cylinder speed x concave clearance interaction as indicated in table 4. From figure 16, mechanical damage differences between the feed rate levels generally increased as the cylinder speed increased from 800 rpm to 1200 rpm. This differential response was indicated by the significant cylinder speed x feed rate interaction in table 4. Thus, at the highest cylinder speed of 1200 rpm, an increase in feed rate from 100 lbs./min. to 300 lbs./min. would have appreciably decreased the mechanical damage, whereas, at the lowest cylinder speed of 800 rpm an increase in feed rate had negligible effect on percentage damage. Although the concave clearance x feed rate interaction was significant, it was only significant at the .05 probability level (table 4). From figure 17, the differences in damage between the levels of feed rate decreased in general with increasing concave clearance.

As indicated by the grand mean threshability (table 3) of 98.37%, values of threshability obtained over the experiment were high. From Appendix VI, the lowest value was 94.41% and the highest value was 99.47%. Perfect threshability (100%) was not achieved but in practical

terms, threshability values over 99% would seldom be attained. The generally high threshability values obtained over the experiment were due to the crop condition. The average moisture content (wet-basis) of the crop used was 10.4% which indicated the dry condition of the crop. Under dry conditions, the kernels and straw were brittle and the heads were easily threshed.

From figure 13, threshability increased rapidly with increasing cylinder speed from 800 to 1000 rpm (4396 ft./min. to 5495 ft./min.). From 1000 to 1200 rpm (5495 ft./min. to 6594 ft./min.), the threshability curve began to level out. This would imply that there were some grain kernels which were easier to remove from the ear than others. This contention is supported by the literature[34]. The larger, riper kernels in the head are easily removed even at lower cylinder speeds while the smaller kernels are harder to remove. In order to remove the last few remaining kernels from the ear in an attempt to reach 100% threshability, a substantial increase in cylinder speed would be necessary.

Figure 18 indicated increasing kernel damage with increasing cylinder speed especially between 1000 and 1200 rpm. The grand mean damage was 6.5% (table 5) and the range was 1.0% to 16.0% as given in Appendix VII. The dry condition of the threshing material (10.4%) made the kernel more susceptible to shattering and chipping[34]. Figure 19 indicates the change in percent damage with a change in concave clearance and figure 20 indicates the change in percent damage with a change in feed rate. It can be seen from the graphs that mechanical damage was influenced more by changes in concave clearance than feed rate with cylinder speed showing the greatest change over the levels considered.

The regression equation derived for threshability in terms of cylinder speed, concave clearance and cylinder speed x concave clearance interaction was considered to be valid within the range of values used in its determination. The equation could be used as a prediction equation for evaluating cylinder performance in terms of the independent variables contained in the expression. A necessary limitation of the equation would be that it is only valid when crop variables are similar to those used in this experiment since moisture content, grain to straw ratio and varietal differences are important crop parameters influencing threshability[3].

The relationship expressing percentage mechanical damage in terms of cylinder speed and cylinder speed x concave clearance interaction holds for the values used in its determination subject to the same limitations concerning crop variables as stated for threshability.

5.2 Minimization of Grain Loss

The regression equations determined for percentage threshability and percentage mechanical damage described the performance of the cylinder-concave unit in the laboratory threshing unit as described in the materials section (3.2.2). The definition of total grain loss including unthreshed heads and all damaged kernels was valid for the laboratory threshing unit since it had no rethreshing or cleaning facilities. However, in a practical situation, the field harvester is an entire unit and includes rethreshing as well as cleaning facilities. Thus, total grain loss from a combine in the field would consist of different terms than those used in a total loss definition for the laboratory threshing unit. The damaged kernels and unthreshed heads would occur in the field combine but some of the unthreshed portion

would be recovered by the rethreshing unit. In the field, additional losses such as free seed loss over the shoe and the straw-walker also occur. Thus, it was not possible to equate total loss from the laboratory unit to total loss from a field combine. However, it was possible to equate the cylinder loss from a field combine to the total loss as defined for the laboratory unit. The cylinder loss for a field combine would include only the unthreshed heads and the damaged kernels produced by the cylinder-concave unit without regard to the material after it leaves the cylinder-concave unit. This is the same loss that was defined for the laboratory threshing unit.

Upon analysis of the total loss equation (Y_L) as determined from the results of the research, it was found that the levels of the parameters considered did not give an optimum situation. The results did indicate that future experiments should consider cylinder speeds below 800 rpm (4396 ft./min.) which was the general area in which an optimum situation of high threshability and low kernel damage could occur. General recommendations[42] on settings of cylinder speed and concave clearance for combines indicated a cylinder speed of approximately 5300 ft./min. and a concave clearance of 3/4 in. for the front and 1/8 in. for the rear. These recommendations were for threshing wheat under very dry conditions and were based on a summary of recommendations found in operator's manuals published by combine manufacturers. In terms of this research, 5300 ft./min. would indicate a cylinder speed of 980 rpm using the laboratory threshing unit. According to the findings of this research, the cylinder speed for an optimum situation of high threshability and low kernel damage would be below 800 rpm cylinder speed. This would imply that the general

recommendations as found in operator's manuals for setting cylinder speed,were high.

It is believed that farmers set the threshing parameters on their combines according to the operator's manual or by considering the threshability without due regard to mechanical kernel damage. If this is the case, they are probably using cylinder speeds which are unnecessarily high and the result could be excessive damage kernels and high threshability.

5.3 Comments

The results obtained from the analysis of the data collected in this research study would be useful:

1. in predicting combine cylinder performance as it pertains to threshability and mechanical damage using the regression equations obtained.
2. for determining the general settings for cylinder speed and concave clearance when threshing wheat under dry conditions.
3. in analyzing threshing problems in the field. The investigation indicates the important threshing parameters affecting threshability and grain damage. Problems in the field concerning excessive kernel damage or under threshing could be approached with prior knowledge of the probable setting changes required in order to overcome the problem.
4. in deciding what level of threshability is desirable with a view towards minimizing grain loss in the form of unthreshed heads and damaged kernels.
5. for indicating the mechanical parameters that should be studied in future experiments concerning threshing.

6. CONCLUSIONS

Conclusions that can be drawn from this investigation concerning laboratory threshing experiments are:

1. Threshing experiments can be conveniently carried out in the laboratory using a stationary threshing unit. Variations in weather conditions that may influence results in the field are completely eliminated and strict control over all aspects of experimental procedure are possible.
2. Cleaning the grain samples collected from the threshing unit is the most time consuming aspect of the procedure in laboratory threshing experiments. At the same time, it is the most critical step since measurements are based on the grain weights collected using the cleaning unit.
3. Simulation of field conditions with regard to crop presentation to the threshing unit can be accomplished using feed conveyor such as the one described in this research.

Conclusions that can be drawn from this research with regard to the results obtained are:

1. The mechanical parameters causing significant variation in percentage of wheat threshed are cylinder speed and concave clearance.
2. The mechanical parameters causing significant variations in percentage mechanical damage to wheat are cylinder speed, concave clearance and feed rate.

3. Threshability can be expressed in terms of the mechanical parameters by a regression equation of the form:

   $$Y_T = A_0 + A_I X_S + A_2 X_S^2 + A_3 X_C + A_4 X_S X_C$$

   where Y_T is percentage threshability, A_0 is a constant and A_1, A_2, A_3, A_4 are regression coefficients. X_S and X_C are the mechanical parameters of cylinder speed and concave clearance respectively.

4. Mechanical damage can be expressed in terms of the mechanical parameters by a regression equation of the form:

   $$Y_D = B_0 + B_1 X_S + B_2 X_S^2 + B_3 X_S X_C$$

   where Y_D is percentage mechanical damage, B_0 is a constant and B_1, B_2, B_3 are regression coefficients. X_S and X_C are the mechanical parameters of cylinder speed and concave clearance respectively.

5. A level of the variables considered in this research that would result in an optimum situation of high threshability and low kernel damage was not obtained.

6. Future threshing experiments that consider an optimum situation of high threshability and low kernel damage as one of the objectives, should include cylinder speeds below 4300 ft./min.

7. In practical situations, combine operators should consider kernel damage as well as threshability in setting mechanical threshing parameters when combining dry wheat.

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8. APPENDICES

APPENDIX I: List Of Treatment Combinations.

Trial Number	Cylinder Speed (X_s) - rpm.	Concave Clearance (X_c)- in.	Feed Rate (X_F)-lbs./min.
1	1200	1/4	300
2	1200	1/4	200
3	1200	1/4	100
4	1200	1/2	300
5	1200	1/2	200
6	1200	1/2	100
7	1200	3/4	300
8	1200	3/4	200
9	1200	3/4	100
10	1100	1/4	300
11	1100	1/4	200
12	1100	1/4	100
13	1100	1/2	300
14	1100	1/2	200
15	1100	1/2	100
16	1100	3/4	300
17	1100	3/4	200
18	1100	3/4	100
19	1000	1/4	300
20	1000	1/4	200
21	1000	1/4	100
22	1000	1/2	300
23	1000	1/2	200
24	1000	1/2	100
25	1000	3/4	300
26	1000	3/4	200
27	1000	3/4	100
28	900	1/4	300
29	900	1/4	200
30	900	1/4	100
31	900	1/2	300
32	900	1/2	200
33	900	1/2	100
34	900	3/4	300
35	900	3/4	200
36	900	3/4	100
37	800	1/4	300
38	800	1/4	200
39	800	1/4	100
40	800	1/2	300
41	800	1/2	200
42	800	1/2	100
43	800	3/4	300
44	800	3/4	200
45	800	3/4	100

Appendix II: Randomized Order Of Execution Of The Trials.

Replicate 1	Replicate 2	Replicate 3	Replicate 4
28	4	20	25
23	35	9	14
27	26	27	39
21	28	43	11
38	18	8	22
39	19	34	30
17	2	32	17
34	8	7	26
43	43	35	13
26	27	1	24
5	14	10	19
22	11	44	9
25	13	17	45
6	31	24	2
40	32	23	15
12	1	33	37
20	36	6	18
2	41	37	28
32	7	41	43
35	17	22	1
9	38	18	29
4	3	21	16
15	10	16	12
31	22	2	8
7	42	28	3
8	39	31	7
37	5	19	20
3	30	14	4
36	16	12	21
29	24	4	6
19	34	36	32
11	33	15	44
30	40	38	10
10	44	42	5
44	37	39	23
14	12	30	38
33	9	13	41
42	20	25	42
1	6	45	33
16	23	5	27
45	29	40	40
13	25	3	35
24	21	26	34
41	15	29	36
18	45	11	31

Appendix III: Weight of Initial Grain Catch (W_1) lbs.

	W_1			
Trial Number	Replicate 1	Replicate 2	Replicate 3	Replicate 4
1	38.58	34.75	40.60	32.09
2	38.13	38.28	38.59	41.59
3	36.90	36.06	40.15	36.50
4	36.75	38.18	35.20	33.50
5	38.83	38.98	33.01	37.24
6	34.00	42.62	35.08	31.24
7	37.98	40.44	34.76	33.36
8	37.16	37.91	33.53	34.98
9	41.92	37.08	35.74	33.10
10	35.53	39.82	33.53	33.06
11	37.99	36.66	32.06	35.02
12	43.38	39.87	37.18	38.01
13	35.98	46.49	32.87	34.68
14	35.41	34.49	35.59	34.20
15	38.94	38.32	35.34	39.88
16	36.69	35.14	35.89	31.84
17	39.79	38.52	38.44	34.84
18	34.36	38.19	38.74	31.30
19	37.35	34.96	38.60	36.35
20	33.55	42.59	35.58	34.76
21	37.76	38.78	39.90	34.58
22	32.94	37.24	37.60	33.02
23	39.61	41.86	36.03	32.68
24	38.32	37.31	37.36	38.40
25	37.35	39.32	34.15	32.64
26	33.50	33.64	42.64	31.04
27	37.70	38.62	36.70	38.88
28	38.89	36.63	34.92	33.36
29	39.74	39.54	29.87	36.76
30	37.61	34.43	35.63	35.50
31	38.16	33.23	40.73	35.60
32	36.38	39.12	38.24	32.08
33	34.90	42.28	40.38	32.10
34	38.36	38.31	34.94	38.38
35	42.63	35.37	37.48	35.74
36	29.93	39.74	42.12	31.52
37	35.23	37.18	37.98	38.84
38	37.24	43.18	32.77	31.72
39	41.53	37.26	33.87	32.31
40	33.55	39.38	30.95	30.18
41	32.85	38.77	32.61	32.33
42	32.48	35.10	38.80	35.62
43	32.55	33.15	34.70	30.72
44	31.27	36.63	30.20	33.30
45	33.35	34.59	37.82	31.31

Appendix IV: Weight of Rethresh Grain Catch (W_2) lbs.

	W_2			
Trial Number	Replicate 1	Replicate 2	Replicate 3	Replicate 4
1	0.21	0.25	0.30	0.20
2	0.31	0.30	0.26	0.22
3	0.25	0.28	0.26	0.20
4	0.36	0.33	0.34	0.28
5	0.39	0.38	0.28	0.30
6	0.34	0.40	0.34	0.26
7	0.40	0.41	0.38	0.32
8	0.38	0.38	0.36	0.32
9	0.42	0.37	0.36	0.30
10	0.32	0.32	0.28	0.25
11	0.37	0.31	0.26	0.26
12	0.38	0.32	0.31	0.28
13	0.45	0.52	0.38	0.40
14	0.48	0.44	0.40	0.38
15	0.50	0.45	0.40	0.42
16	0.55	0.50	0.43	0.50
17	0.57	0.54	0.45	0.48
18	0.50	0.53	0.46	0.43
19	0.40	0.38	0.38	0.38
20	0.40	0.46	0.36	0.34
21	0.41	0.42	0.40	0.33
22	0.55	0.49	0.46	0.60
23	0.62	0.55	0.46	0.55
24	0.62	0.48	0.47	0.68
25	0.72	0.62	0.45	0.64
26	0.64	0.55	0.53	0.58
27	0.69	0.61	0.47	0.68
28	0.40	0.58	0.52	0.33
29	0.59	0.59	0.40	0.46
30	0.78	0.46	0.51	1.01
31	0.85	0.51	0.88	0.60
32	0.82	0.59	0.72	0.56
33	0.81	0.65	0.62	0.74
34	1.08	1.02	0.94	1.03
35	1.32	0.90	0.82	1.00
36	0.98	1.02	1.21	1.06
37	0.82	0.68	0.83	0.89
38	0.89	0.72	0.72	0.89
39	0.99	0.79	0.64	0.66
40	0.82	1.01	0.78	0.90
41	0.82	0.98	0.80	0.93
42	0.82	0.75	0.90	0.80
43	1.59	1.16	1.12	1.82
44	1.12	1.14	0.94	1.76
45	1.14	0.93	1.12	1.72

Appendix V: Grain Moisture Contents (Wet Basis)

	%			
Trial Number	Replicate 1	Replicate 2	Replicate 3	Replicate 4
1	9.9	10.7	9.4	10.8
2	10.5	10.3	9.8	10.6
3	10.1	10.6	9.6	10.0
4	9.7	9.9	9.8	11.0
5	10.3	10.1	9.9	10.5
6	10.3	10.9	10.5	10.2
7	11.3	9.8	10.5	10.5
8	10.0	10.8	9.8	10.2
9	11.4	11.0	10.1	10.9
10	9.9	10.3	10.9	9.9
11	10.2	9.8	10.5	10.4
12	10.0	9.4	11.0	10.9
13	10.6	10.5	10.3	11.2
14	9.9	10.8	10.3	10.8
15	9.6	10.5	10.2	11.0
16	9.6	10.4	11.0	10.4
17	10.5	10.6	10.5	10.5
18	9.5	10.3	10.7	10.9
19	10.2	10.4	10.6	10.9
20	10.0	10.8	10.5	10.7
21	10.3	10.2	10.7	10.8
22	9.5	10.2	10.5	10.5
23	10.1	10.9	10.4	10.5
24	10.2	10.2	10.6	10.8
25	10.5	9.8	10.9	10.2
26	11.1	9.1	10.3	10.9
27	10.0	10.3	10.5	10.4
28	10.4	10.8	10.7	10.8
29	10.2	10.1	10.5	10.5
30	10.1	10.4	10.4	10.7
31	10.0	10.5	10.6	10.7
32	10.9	10.5	10.5	11.0
33	11.1	10.5	11.0	10.6
34	10.4	10.6	10.3	10.4
35	10.3	10.3	10.5	10.6
36	9.5	10.9	10.9	10.7
37	10.8	10.4	10.3	10.5
38	9.8	10.6	10.2	10.8
39	10.7	10.2	10.1	10.0
40	10.4	10.3	10.6	10.0
41	10.5	10.8	10.6	10.7
42	9.1	10.5	11.0	10.8
43	9.8	10.6	10.9	10.6
44	10.8	9.8	10.9	11.0
45	10.8	9.5	11.0	10.9

Appendix VI: Threshability Values (Y_T) - %

	Y_T			
Trial Number	Replicate 1	Replicate 2	Replicate 3	Replicate 4
1	99.46	99.29	99.27	99.38
2	99.19	99.22	99.33	99.47
3	99.33	99.23	99.36	99.46
4	99.03	99.14	99.04	99.17
5	99.01	99.03	99.16	99.20
6	99.01	99.07	99.04	99.17
7	98.96	99.00	98.92	99.05
8	98.99	99.01	98.94	99.09
9	99.01	99.01	99.00	99.10
10	99.11	99.20	99.17	99.25
11	99.04	99.16	99.19	99.26
12	99.13	99.20	99.17	99.27
13	98.76	98.89	98.86	98.86
14	98.66	98.74	98.89	98.90
15	98.73	98.84	98.88	98.96
16	98.52	98.60	98.82	98.45
17	98.59	98.62	98.84	98.64
18	98.57	98.63	98.83	98.64
19	98.94	98.92	99.02	98.97
20	98.82	98.93	99.00	99.03
21	98.93	98.93	99.01	99.05
22	98.36	98.70	98.79	98.22
23	98.46	98.70	98.74	98.34
24	98.41	98.73	98.76	98.26
25	98.11	98.45	98.70	98.08
26	98.12	98.39	98.77	98.17
27	98.20	98.44	98.73	98.28
28	98.98	98.52	98.53	99.02
29	98.54	98.53	98.68	98.76
30	97.97	98.68	98.59	97.23
31	97.82	98.49	97.88	98.34
32	97.80	98.51	98.15	98.28
33	97.73	98.49	98.49	97.75
34	97.26	97.41	97.38	97.39
35	97.00	97.52	97.86	97.28
36	96.83	97.50	97.21	96.75
37	97.72	98.20	97.86	97.76
38	97.67	98.36	97.85	97.27
39	97.67	97.92	98.14	98.00
40	97.61	97.50	97.54	97.10
41	97.56	97.53	97.60	97.20
42	97.54	97.91	97.73	97.80
43	95.34	96.62	96.87	94.41
44	96.54	96.98	96.98	94.48
45	96.69	97.38	97.12	94.80

Appendix VII: Mechanical Damage (Y_D) - %.

	Y_D			
Trial Number	Replicate 1	Replicate 2	Replicate 3	Replicate 4
1	12.3	11.9	13.9	12.6
2	12.6	12.5	14.5	15.3
3	15.5	15.9	16.0	14.5
4	12.0	12.1	10.9	9.8
5	13.7	11.6	12.5	11.9
6	14.8	13.6	12.9	13.3
7	10.1	9.8	10.6	9.5
8	10.9	10.5	11.2	10.8
9	11.3	10.9	11.0	11.5
10	8.1	9.2	8.4	8.5
11	10.2	9.9	10.9	8.9
12	9.7	10.1	11.2	10.3
13	7.2	7.6	6.9	7.0
14	8.0	7.9	8.2	8.5
15	8.2	8.0	7.5	8.8
16	6.4	6.0	6.5	6.2
17	6.4	6.2	6.1	6.8
18	6.5	6.4	7.2	7.6
19	5.4	5.7	4.9	5.8
20	5.8	5.9	5.8	6.0
21	6.9	7.3	6.8	6.8
22	5.2	5.0	5.4	5.0
23	6.1	5.5	5.8	5.7
24	6.4	6.0	6.3	6.2
25	4.9	5.1	4.6	4.3
26	4.6	4.8	4.9	4.5
27	6.0	5.8	5.2	5.0
28	4.4	3.8	4.2	4.1
29	4.3	4.5	4.9	5.2
30	4.8	5.0	5.0	4.8
31	3.9	3.7	2.9	2.9
32	3.9	4.0	3.9	4.1
33	4.0	4.1	4.3	4.1
34	3.3	3.6	2.2	2.0
35	3.1	3.3	2.6	2.3
36	4.0	3.9	3.6	2.9
37	3.8	4.1	4.0	4.5
38	3.8	4.0	3.9	3.9
39	4.1	4.2	3.6	4.3
40	3.1	3.0	2.5	2.9
41	2.5	2.9	3.9	3.3
42	2.8	2.8	3.1	3.3
43	2.3	1.6	1.2	1.0
44	1.7	1.8	1.8	1.6
45	1.9	2.1	1.6	1.9

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